CREEP OF PORTLAND CEMENT PASTE

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by

W. G. MULLEN

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

CREEP OF PORTLAND CEMENT PASTE

TO: K. B. Woods, Director
Joint Highway Research Project

September 27, 1963

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-47H
File: 4-6-8

A Final Report entitled "Creep of Portland Cement Paste" is attached. It has been authored by Mr. Wesley G. Mullen, a Graduate Fellow on our staff. The research was directed by Professor W. L. Dolch of our staff and the report was used by Mr. Mullen as his disertation for the Ph.D. degree.

The project was approved by the Board on February 14, 1962. As Mr. Mullen was on a fellowship granted by ASTM the primary cost to the Project of this research was for some supplies, a small amount of equipment, and duplication of the report.

The report is presented to the Board as information and for the record. Copies of the report may also be made available to the organization granting Mr. Mullen the fellowship.

Respectfully submitted,

Harold L. Michael
Harold L. Michael, Secretary

HLM:bc

Attachment

Copies:

F. L. Ashbaucher
J. R. Cooper
W. L. Dolch
W. H. Goetz
F. F. Havey
F. S. Hill
G. A. Leonards
J. F. McLaughlin
R. D. Miles
R. E. Mills
M. B. Scott
J. V. Smythe
E. J. Yoder

Final Report

CREEP OF PORTLAND CEMENT PASTE

by

Wesley G. Mullen
Graduate Fellow

Joint Highway Research Project

File No: 4-6-8

Project No: C-36-47H

Purdue University

Lafayette, Indiana

September 27, 1963

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To three gentlemen, whose example and whose personal and professional interest and help have profoundly influenced and aided my professional career, special acknowledgment is made in the form of dedication of this work:

To the memory of

Colonel R. A. Marr, Jr.,
Head of the Department of Civil Engineering, 1941-55,
Virginia Military Institute

To

Mr. Stanton Walker
Director of Engineering, Emeritus,
National Sand and Gravel Association, and
National Ready Mixed Concrete Association

And to

Mr. C. S. Mullen
my father and
Chief Engineer, retired
Virginia Department of Highways

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ABSTRACT

Mullen, Wesley Grigg. PhD., Purdue University, June 1963. Creep of Portland Cement Paste. Major Professor: William L. Dolch.

The purpose of the investigation reported in this paper has been to contribute to knowledge of the basic creep mechanism associated with portland cement concrete. Specific goals have been to contribute to the evaluation of the seepage and delayed elasticity theories of creep, the relation between creep and shrinkage, and the role of water in creep. Included is a review of the literature and a restatement and discussion of the various theories of creep.

It was felt that creep is controlled almost entirely by the cement paste, and investigations were limited to this phase. Since it has been observed that the rate of attainment of ultimate creep is inversely proportional to some function of the specimen size, it was thought desireable to work with small homogenous paste specimens to simplify control and to accelerate testing progress. The specimen selected was a hollow cylinder with a wall thickness of 0.1 inch, an outside diameter of 1.1 inches, and a height of 6 inches. Specimens were cast on a vibrating table and special measures including cycles of inversion and vibration were undertaken to insure uniform density with respect to height.

A 50X bifilar linear traversing microscope was used to measure strains registered on a periscope adaptation of the Monfore hypodermic

needle tube strain gage. Two gages were attached over four inch gage lengths on each specimen. The periscope adaptation was an offsetting feature to allow immersion of the specimen without immersion of the fiducial marks. Loading was by dead weight in a lever type rig. Tests were conducted inside a temperature chamber controlled at 25 ± 0.1 C, and in an air conditioned laboratory. Specimens were enclosed in individual environment containers for testing.

Test specimens of four water cement ratios, 0.30, 0.33, 0.40 and 0.45, were loaded at 29 days to 0.4 f'_c in saturated and oven dry conditions. Oven drying was at 110 C to constant weight. Also, there were specimens that were resaturated under load. Saturation was maintained by continuous immersion in lime water, and the oven dry condition was maintained by immersion in a desiccated, carbon dioxide free, nitrogen bath under slight pressure. Load duration varied up to 1300 hours depending upon the exposure. Other tests are reported in addition to those mentioned above.

It was found that the time dependent strain data for saturated specimens exhibited three fairly distinct zones of curvature. The existence of these zones has been taken as evidence that there is more than one mechanism of creep functioning, and that the change from one zone to another is indicative of the ascendency of one mechanism of creep and the attrition of another.

Also, a scallop effect was found in the data for all individual saturated specimens. This scallop effect was most noticeable in the first of the three creep curve zones mentioned above, and is attributed to a cyclic combination of the seepage, delayed elastic, and mechanical reorientation theories of creep mechanism.

One of the most significant findings was that in every instance of loading, hardened paste specimens that were oven dried at 110 C to constant weight did not creep at all. This is regarded as evidence that there is an upper limit on time dependent deformation of hardened portland cement paste that is independent of applied load. This upper limit is equal to the drying shrinkage and is called the absolute creep potential.

Upon the resaturation of oven dried specimens under load, a quasi-equilibrium level was found that is associated with the so-called equilibrium creep potential. The equilibrium creep potential is the residual value of unrecovered shrinkage plus any delayed elastic deformation when the expansion of an oven dried specimen has reached its maximum value after having been rewetted to a given humidity and under a given load. The equilibrium creep potential is therefore load and humidity dependent. The maximum value of the equilibrium creep potential is the absolute creep potential.

Further, the absence of creep when all shrinkage has taken place suggests that creep and shrinkage have the same mechanism and that creep is load induced shrinkage.

INTRODUCTION

Statement of the Problem

Continued deformation under sustained loading, better known as creep, has long been observed in portland-cement concrete and mortars and has been reported in the literature since about 1900. Early concern developed with recognition of possible undesirable stress redistribution effects of creep on reinforced concrete structures, and led to the ACI column investigation at Lehigh University and University of Illinois circa 1930. Column design formulas were the result of this work. (1)*

The allowance for creep losses in prestressed concrete design of 15 to 20 percent is well-known and results in increases of cross section and dead load, thereby limiting the competitive position of prestressed concrete for highway bridges and structural components.

Although creep measurements have been made for 60 years, little is known of the actual mechanism despite a number of seemingly plausible theories that have been advanced and the observation of a number of factors that affect creep behavior. It is possible that reductions in prestressing losses could result from a better understanding of the mechanism of creep.

The problem then becomes one of discovering the basic mechanism or mechanisms of creep and, if possible, the means of controlling these

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*Numbers in parenthesis refer to entries in list of references.

mechanisms. It is toward this ultimate goal that the investigation reported herein has been directed.

Purpose of the Investigation

The overall goal of this investigation has been to contribute to knowledge of the basic creep mechanism to the end that creep may be controlled as a phenomenon associated with portland cement concrete.

The specific goals of this investigation have been to evaluate the seepage and delayed elasticity theories of creep, the relation between creep and shrinkage, and the role of water in creep.

Review of the Literature

General

The phenomenon of creep and shrinkage in concrete was first investigated in this country in the early part of this century and was brought to the attention of the engineering profession through the work of W. K. Hatt, D. A. Abrams, I. H. Woolson (2, 3, 4) and others. Since that time extensive experimental data have been published that generally confirm the observations of these early investigators.

Research of the literature quickly reveals that, until recently, most creep investigations have involved long-time measurements on fairly large concrete test specimens, and, in a number of cases, full size components and field installations (3). Often creep observations were incidental to the observation of other properties. Investigations reported have included numerous variations of mix proportions, aggregate type, magnitude and duration of loading, maturity at time of loading, temperature - humidity environment, and many other factors. There has -

been no truly integrated pattern of testing, and, for the most part, investigations have served mainly to establish a general feeling for the creep characteristics of concretes, to imply that concrete creep is primarily controlled by the creep characteristics of the cement paste, and to indicate that accurate measurement techniques must be developed or adapted to implement progress in determining the mechanism of creep. Quantitatively, many previous investigations must be disregarded in establishing a creep mechanism owing to lack of sensitivity of measurements and failure to control or to take into account variables such as moisture content, vapor pressure, aggregate characteristics, curing and end restraints.

A great deal of effort has been devoted to curve fitting in the literature and to the establishment of complex rheological models to explain creep behavior. These equations range from simple to complex and are generally hyperbolic or exponential in form. Some attempt merely to fit the data presented in a given research, while others attempt to establish equations to include all common mixture design and material source variables as well as variables of age and environment. The goal of the more comprehensive of these efforts is to allow predictions of creep behavior without the necessity for conducting laboratory investigations. Invariably, however, these equations contain one or more constants or factors which must be evaluated by experiment for a given concrete. In other words, the creep curve must be obtained by test before the theoretical expression may be evaluated.

Sources

Most papers reveiw the literature to some extent and a few are

devoted entirely to summarizing previous work. Two fairly recent reviews are by Neville (5) and Fluck and Washa (6). Bibliographies from the Portland Cement Association (7), through 1953, and by Corley (8), through 1957, contain extensive references on creep. Reference (7) contains two lists of references, and one of these is annotated. In addition, recent papers by L'Hermite (9), Vaishnav and Kesler (10), and Hansen (11, 12), in rather extensive bibliographies record many recent articles and some published as late as 1962.

Summary of Creep Phenomena

Fluck and Washa (6) have reviewed and summarized the literature on creep through 1957 and have compiled a comprehensive bibliography. Results of investigators have been generalized to indicate that many variables seem to affect the creep rate and the total creep. Included in these factors, among others, were mixture design, material selection, manufacture, and curing. Some of their conclusions were: creep of concrete increases with increase of volume of cement paste or increase of water-cement ratio; creep decreases as concrete maturity increases; saturated concrete creeps more than dry concrete, excluding shrinkage; and small specimens creep more than large ones, a size effect. Also, they reported that the creep rate increases with the magnitude of load; creep has been measured for a twenty-five year period of sustained load application; and air entrainment has no appreciable effect on creep. In addition, they reported that creep has been observed for stresses as low as one percent of ultimate strength, an implication that there is no threshold stress value for initiation of creep.

Theories of Creep

Neville (5) has reviewed the various theories of creep and has grouped them into five categories as follows:

Mechanical deformation
Plastic (crystalline flow)
Viscous
Seepage
Elastic after effects

Vaishnav and Kesler (10) have used the following grouping into eight categories for what are essentially the same theories:

Crystalline flow
Seepage or gel water flow
Viscous flow of cement paste
Delayed elasticity
Surface tension effect
Tendency of maximum stability
Non-uniform shrinkage
Internal rupture

Polivka and Best (13) implied that creep may be, in part, thermally activated in a report of some tests on hydrated tricalcium silicate.

Mechanical Deformation. Neville (5) attributes the mechanical deformation theory to Freyssinet (14) who explained creep as due to internal stresses that result from changes in capillary sturcture in the cement paste due to load. It was implied that this creep is completely reversible and recovery is caused by pressure differences that develop between the water and air phases upon removal of load. In other words,

movement is elastic but is delayed upon loading by pressures that develop between the water and air phases of the capillaries. Recovery is accomplished by surface tensions that develop in the water phase upon removal of the load. Freysinnet in a later work (14a) attributed part of creep to tendency of maximum stability through particle rearrangement under load, and this part is irrecoverable. Vaishnav and Kesler (10) have divided Freyssinet's hypothesis into surface tension effect and tendency of maximum stability, and they described the surface tension effect hypothesis as a delayed elasticity effect. Corroboration for the surface tension effect was not found in the literature search.

Plastic or Crystalline Flow. In some of the original papers creep was called plastic flow because of the similarity of the observed effects to time dependent deformation observed in metals. Plasticity observed in metals has been attributed to intra-crystalline slip along planes in the crystal lattice. With passage of time and accumulation of observations it became evident that if crystalline flow is a mechanism in creep, it is not the only one, and use of the word creep has gained ascendency as a description of these phenomena.

Viscous Flow of Cement Paste. This theory states, in effect, that creep is the viscous movement of particles over one another in a cement paste matrix which is actually a liquid. Reiner (15) was one of the early proponents of this viscous theory but has indicated his earlier position was erroneous. Freudenthal and Roll (16) have proposed that the paste is a viscous liquid which crystallizes with passage of time until all flow is blocked by the solid crystal structure.

Seepage or Gel Water Flow. In this theory creep is ascribed to

gain or loss of water from the gel. This theory was probably first proposed by Lynam (17) and has gained considerable support. The seepage theory states that when load is applied to concrete, fluid pressures are induced that cause the migration of gel water and resulting volume changes that are measured as creep.

Delayed Elasticity. In its simplest form delayed elasticity is elastic deformation that would have occurred instantaneously upon application of load except for some restraining effect which diminishes with time. One explanation which has been advanced is that in the saturated paste structure, initial load is borne by the water phase and this is followed by transfer of load to the elastic paste skeleton as the pore pressure diminishes with time. The transfer of load causes additional elastic deformation. Delayed elastic recovery may be described in the same way. The paste skeleton cannot expand elastically until negative pore pressures induced upon removal of load are dissipated.

Non-Uniform Shrinkage. Maney (18) has proposed that observed creep is actually a shrinkage effect and length variations called creep are due to non-uniform shrinkage between interior and exterior of the test specimen upon drying. The creep that is observed at the specimen surface is actually a delayed elasticity effect induced by adjustment of differential shrinkage with the passage of time. Maney, thus, denied the existence of creep.

Internal Rupture. It may be postulated that load causes micro-fractures and local rupture of bonds between paste particles. Particles so affected reorient to positions of maximum stability, making this theory a variation of the tendency of maximum stability and mechanical

deformation theories.

Summary. Theories of creep may reasonably be grouped into the following general categories:

Seepage or gel water flow
Delayed elastic effects
Viscous flow of paste
Plastic or crystalline flow
Mechanical reorientation of particles

Creep Mechanism

Just as unanimity of opinion does not exist in proposing the various theories of creep, there is some divergence of opinion in the acceptance of a theory or combination of theories to explain the creep mechanism. None of the theories advanced truly explain all aspects of creep and none has been proven. All have some merit and some support can be found in the literature for most of these theories. Some investigators as Vaishnav and Kesler (10) propose integrated theories.

One of the earliest investigators of the creep phenomenon was T. T. Quirke (19) who stated that,

> "-----part of the deformation may be permitted by the progressive destruction and reformation of an unstable amorphous hydrate"

and

> "-----part by the fact that cement is soft and slightly plastic material which is kept plastic by the amount of water absorbed by the colloidal hydrated constituents."

An observation of similar nature was made by C. G. Lynam (17) when he stated,

> "-----except for hydration, the gain or loss of water from the gel is the fundamental cause of volume changes due either to moisture variation in the surrounding media or to sustained load."

According to Reiner (15),

> "-----creep is not a slow viscous flow, but a delayed-elasticity effect-----."

Reiner stated that this is a reversal of his earlier belief that creep was attributable to viscous flow. Freudenthal and Roll (16) indicate that creep is due to seepage consolidation, viscous flow of paste, delayed-elasticity effect and localized fracture. Lyse (20), Ross (21) and others differentiate between shrinkage and creep while Fluck and Washa (6) in their summary paper have included shrinkage as a part of creep. Most investigators who differentiate between creep and shrinkage do so by exposing companion specimens without load to the same temperature-humidity environment as the loaded specimens. After observing the volume change of both, which in most cases is measured as a length change, the change of the unloaded specimen is called shrinkage and is deducted from the change of the loaded specimen and this difference is called creep.

Maney (18) attributed creep to differential shrinkage between the inside and outside parts of the specimen, and when this shrinkage was observed by measurements at the specimen surface only, a time dependent length change was observed. Maney stated that this change was a delayed elastic effect due to the differential shrinkage mentioned, and it was not due to creep. This amounted to denying the existence of creep as it is ordinarily understood, and his basis for denying creep was failure to prove the expulsion of water in accordance with the seepage theory through before and after weighings. Critics of Maney's findings question the sensitivity of his weighings in detecting the small water loss postulated to cause creep.

Lorman (22) who adhered to the seepage or gel theory of creep, stated,

> "Thus, except for the effect of hydration, gain or loss of adsorbed water from the gel appears to be the basis of volume changes resulting from ambient moisture variations or from sustained pressure. The gel may be considered as having microscopic pores; with the removal of water the pore spaces collapse and the gel shrinks,------. This process is dependent upon frictional resistance to flow of water along the capillary channels which permeate the mass of concrete."

Some investigators have approached the investigation of creep phenomena through work with mortar and pastes.

Glucklich and Ishai (23), reported creep tests on mortar beams positioned vertically and loaded as cantilevers. In a second paper (24) these authors reported post three day results of torsion tests of dry cylindrical specimens for which no creep was observed. Creep was attributed to migration of water within the voids of the specimen.

Hrennikoff (25) in incremental loading and unloading tests of cement paste observed that creep tended to be a one dimensional effect and that dry paste exhibited little creep. In a second paper (26) Hrennikoff reported that kerosene, alcohol, and lubricating oil did not cause swelling of dried cement paste specimens. However, when one of these non-water-saturated specimens was placed in water, swelling occurred indicating a desire on the part of the water to displace the other liquid from gel surfaces. Hrennikoff refered to this phenomenon as the active water theory of swelling. The implication here seemed to be in support of seepage or gel water mechanism of creep. Namely, the "active water" in adsorbing onto the gel skeleton surfaces exerted a swelling pressure and actually caused swelling or dilation of the gel structure. Conversely, drying or loading caused reversal of the

adsorption processes, removing the "active water" toward pressure equilibrium and a resulting negative volume change.

Relevant Non-Creep Studies

Investigations of the properties of hardened cement pastes, as background for intelligent consideration of the theories of creep, are pertinent to this research. Some of these investigations are the classical work on properties of hardened cement paste by Powers and Brownyard (27), the solid state hydration theory of Hansen (28), and carbonation shrinkage studies by Verbeck (29). Also, there are pertinent papers authored variously by Powers, Hayes, Copeland and Mann on porosity, evaporable water, and permeability of hardened portland cement paste (30, 31, 32).

Approach to the Problem

Discussion

Briefly, it was felt that creep is controlled almost entirely by the cement paste, and that investigations would be limited more profitably to this phase until a mechanism of creep is reasonably well established. Since it has been observed that the rate of attainment of ultimate creep is inversely proportional to some function of specimen size, it was thought to be desirable to work with small homogeneous paste specimens to simplify the control of variables and to accelerate testing progress.

Most important, it was decided to be absolutely necessary to develop or adapt a suitable method of measuring linear displacements of the order

of 5 to 10 microinches per inch on specimens that may be moved about in the progress of testing. An optical method for differential measurement possibly would prove to be the most feasible in this range of measurement accuracy over long periods of time.

Proposed Testing Approach

It was proposed to develop an accurate, stable method of measuring displacements in the order of 3000 microinches per inch to an accuracy of about 5 microinches per inch in small paste specimens subjected to compression stresses of the order of 0.33 to 0.40 of ultimate strength. Specimen shapes proposed were cylindrical shells of about one inch diameter with wall thicknesses of 1/8 to 1/4 inch. Longitudinal gage lengths would be less than specimen length to eliminate end effects.

The cylindrical shell specimen was proposed for three reasons. One reason was to take advantage of a size effect (6) to accelerate the test program through use of a thin wall specimen. Another reason was to test a specimen of as small cross-section as possible in order to allow use of a minimum size lever type dead load rig. Finally, with the small effective specimen size and the small cross section area, it was desired to have a gage length as long as possible to improve accuracy of measurement. The thin walled hollow cylinder seemed to meet all of these requirements.

To implement the evaluation of the seepage and the delayed elasticity theories of the creep mechanism, it was proposed to test specimens in oven dry and saturated exposures.

It was felt that an oven dry specimen under load would show no

creep due to seepage as all evaporable water would have been removed. Any creep observed would be due to some other mechanism. Also, if delayed elasticity is a mechanism of time dependent transfer of load from water phase to solid phase, then, in a specimen without water phase, no delayed elastic effect should be observable. Actually, if specimens could be dried without changing other properties, a dry specimen should display a greater instantaneous elastic deformation than a comparison saturated specimen. The difference between the elastic deformation of the two should represent the delayed elasticity effect attributable to water.

Creep in a saturated exposure would be observed in the absence of shrinkage, while creep of a dried specimen would be observed in addition to completed shrinkage. This could possibly provide a means for evaluation of the interrelation of creep and shrinkage and the role of water in creep.

Volume change due to carbonation would be prevented, and thus eliminated as a variable, by continuous immersion of saturated specimens in lime water, and by insulation of dry specimens in a dry, carbon dioxide free nitrogen bath.

To eliminate temperature as a variable, it was proposed to perform specimen preparation in an air conditioned laboratory and to carry out curing and testing in a controlled temperature closet within this laboratory.

EXPERIMENTAL WORK

Materials

Materials incorporated into the test specimens were an ASTM Type I portland cement from the local market, and deionized water containing less than one part per million equivalent sodium chloride. Characteristics of the cement are shown in Table 1.

Sample Preparation

Molds

It was stated in the introduction that a hollow cylinder seemed to be the most desirable shape for the test specimen. The hollow cylinder has a minimum cross section area to facilitate attainment of the desired stress level with minimum total load application. If the size effect mentioned by Fluck and Washa (6) is valid for cement paste specimens, then use of the thin wall would take advantage of this effect to accelerate testing. Finally, the shape has maximum stability for minimum cross-section area to allow a greater length of specimen and thereby a greater gage length than for a solid cylinder of equal cross-section area.

Two references to the case of hollow cylindrical specimens were found in the literature. Maney (18) tested some hollow concrete cylinders of unspecified manufacture and dimension in support of his non-uniform-shrinkage-effect explanation for the non-existence of creep. Torroja

TABLE 1. CHARACTERISTICS OF CEMENT

Compound	Percent
SiO_2	22.0
Al_2O_3	3.2
Fe_2O_3	4.5
MgO	1.4
SO_3	1.5
Loss on ignition	1.0
CaO	65.3
Total	98.9
Tricalcium silicate	65.7
Dicalcium silicate	13.7
Tricalcium aluminate	1.4
Tetracalcium Alumino ferrite	13.7

Fineness, Blaine meter 3060 sq cm per g

This cement meets the requirements of ASTM Designation: C 150-61, for Type I and Type III cements. Chemical analysis was performed according to ASTM Designation: C 114-61. Fineness was determined in accordance with ASTM Designation: C 204-55.

and de la Pena (33) reported use of hollow "mortar pipes", as they were called, in creep and shrinkage investigations. These specimens were cast by packing and molding mortar by hand with a sharpened straight edge against the inside surface of a two piece stainless steel mold. Specimens were 100 millimeters long and 50 millimeters outside diameter. Wall thickness was 2 millimeters in the barrel but was increased to 3 millimeters at each end by uniform taper for 8 millimeters. The reason given for thickened ends was to prevent failures that had occurred in specimens of uniform cross-section.

It was decided for the investigation reported herein to attempt manufacture of a constant cross-section cylinder with a length to height ratio of approximately 6 to 1, and about one tenth inch wall thickness. Water cement ratios were contemplated of such consistency as to require forming both inside and outside specimen surfaces. Forming such a cylinder was difficult and a major problem was forming of the inside surface. Selection of materials for the mold required careful consideration. It was desired to test a pure cement paste free from admixtures or adulterants. Parting lubricants used on mold surfaces might be absorbed by the paste, and the specimen manufactured thus would not be the specimen desired. Another consideration was that the specimen should have reasonably uniform density from top to bottom.

After several failures and considerable experimentation, a mold, illustrated in various stages of assembly in Figure 1, was selected to form a hollow cylindrical specimen 7 inches long, 1.1 inches outside diameter, and 0.9 inches inside diameter. Nominal wall thickness was 0.1 inches, and the measured cross-section area was 0.301 square inches.

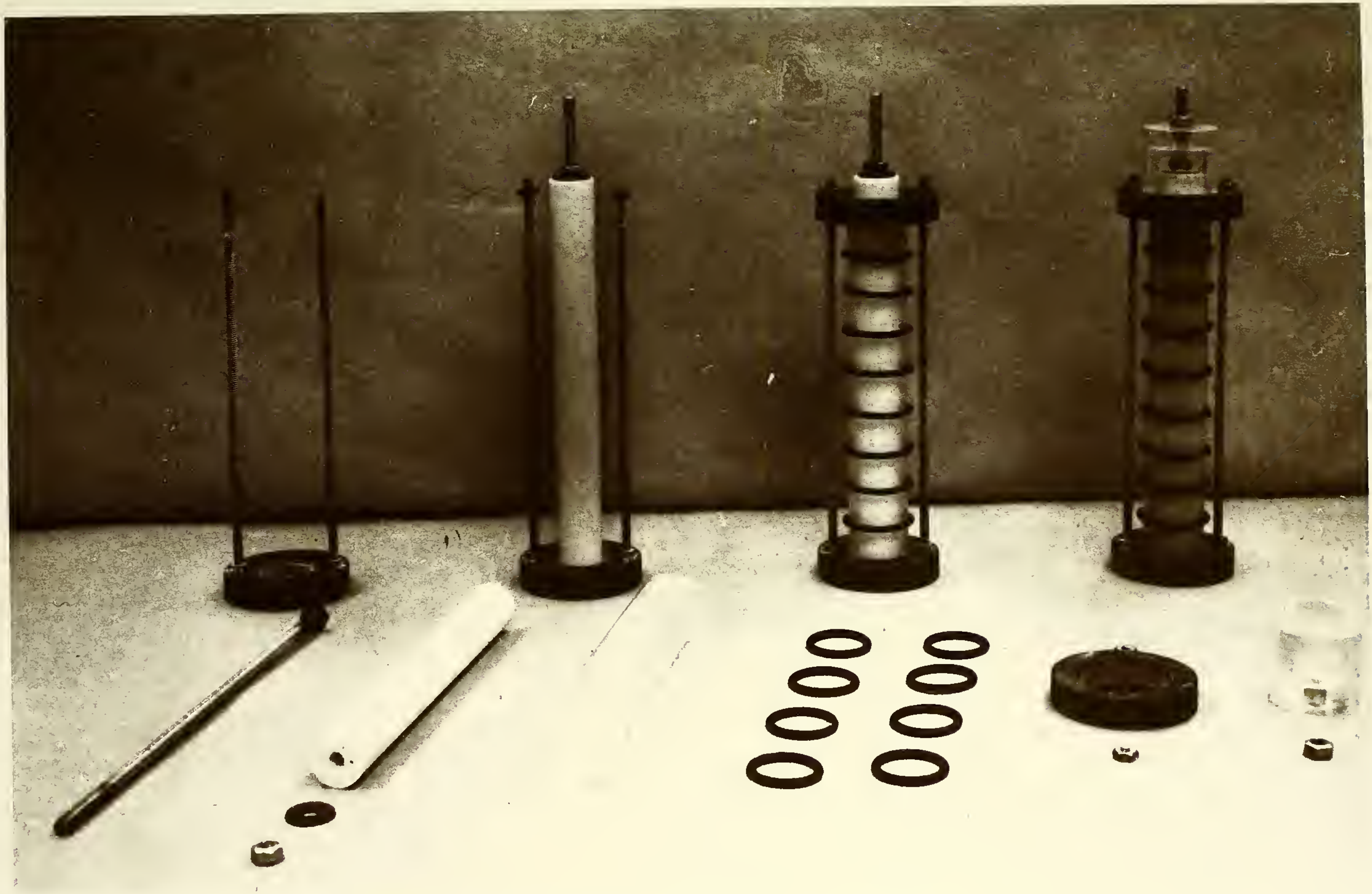

FIG.I TEST SPECIMEN MOLDS

The core to form the inside surface was made of teflon and the outside form was a split plexiglass tube. O-rings were used to hold the split tube closed during specimen casting. The ends of the mold were of laminated bakelite and the mold was provided with a plexiglass stopper to seal it upon completion of filling. Joints between mold parts were sealed with melted paraffin except for the one between the stopper and the bakelite cap which was sealed with a silicone grease. To facilitate its removal after casting, the diameter of the core was pre-expanded a fixed amount before casting by tightening the central bolt shown in Figure 1 to compress the core axially. When the compression was released after specimen casting, the contracted core was easily extracted. Nevertheless, stripping of fragile new specimens was a delicate business, and a special technique had to be developed in order to strip specimens without damage. Mold materials were such that parting lubricants were unnecessary and were not used.

Mixing by Hand

Specimens were mixed by hand in a 250 milliliter stainless steel beaker on a vibrating table* and using a small spatula. Batches consisted of 300 grams of cement and measured water for the desired water-cement ratio. Mixing was continued for from five to ten minutes depending upon the water-cement ratio. Each batch was sufficient to make four specimens with excess material left over.

---

*Syntron Company, Homer City, Pennsylvania

Filling Molds

A sequence of filling the molds was worked out by trial and error in order to insure uniform density of specimens from top to bottom. Molds were filled on the vibrating table four at a time. Paste was placed in three equal lifts, and each lift was rodded with a thin stainless steel rod 25 times before the next lift was placed. Vibration was continuous during the filling and rodding process. Molds were overfilled. When filling was completed vibration was stopped, and the molds were allowed to stand for several minutes. Excess material was then cleaned from the molds, the stopper was placed with the aid of vibration and secured with a nut. A filled, stoppered, mold is shown at the right in Figure 1. Elapsed time from start of mixing to stoppering was varied from 20 to 25 minutes depending upon the water cement ratio.

After stoppering, the molds were subjected to a series of inversion and reinversion cycles each beginning with a two minute period of vibration and followed by a period of rest. The intent of this treatment was to obtain uniform density from top to bottom of the specimens, and to disrupt and reconsolidate bleeding channels. Final reinversion and vibration sequence was concluded by removal of the nut to break the stopper seal and immersion of the entire specimen-mold unit in lime water for curing. Total elapsed time was 70 to 80 minutes.

Success of the inversion-vibration process in obtaining a reasonably uniform density distribution is indicated in Figure 2 and Table 2. It was found that if specimens were stored without first breaking the stopper seal there was a tendency to self desication during the first 24 hours. Breaking the seal before immersion avoided this defect.

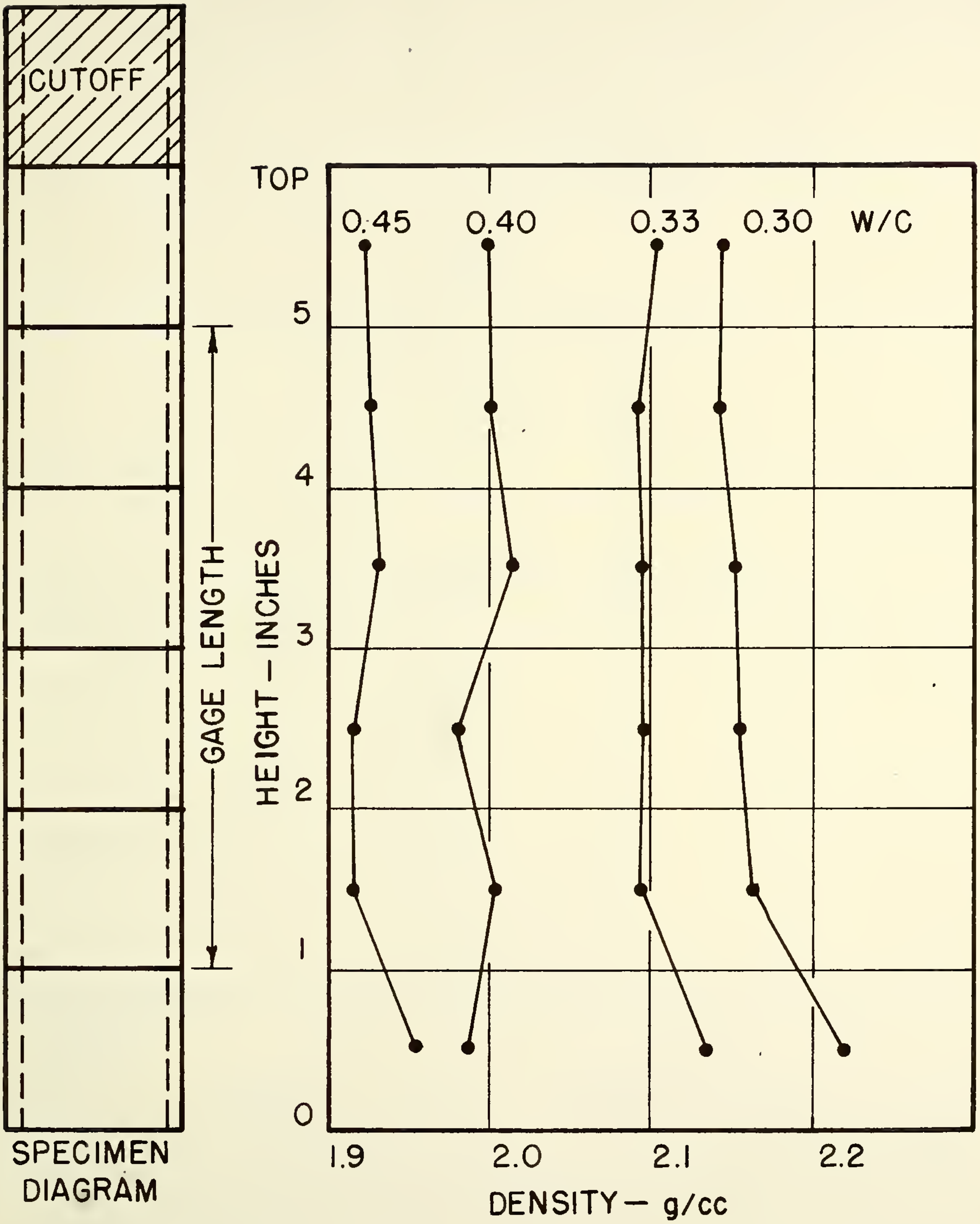

FIG. 2 PASTE DENSITY VS SPECIMEN HEIGHT

TABLE 2

HARDENED PORTLAND CEMENT PASTE DENSITY VS SPECIMEN HEIGHT FOR NOMINAL WATER - CEMENT RATIOS

SEGMENT	SATURATED DENSITY IN GRAMS PER CC			
	0.30 W/C	0.33 W/C	0.40 W/C	0.45 W/C
5"-Top	2.144[a]	2.106	2.000	1.923
4" - 5"	2.141	2.091	2.003	1.925
3" - 4"	2.153	2.097	2.017	1.931
2" - 3"	2.154	2.097	1.991	1.917
1" - 2"	2.163	2.095	2.004	1.916
0 - 1"	2.220	2.134	1.987	1.965
Average Middle 4 in.	2.153	2.095	2.004	1.923

[a] All values are averages of two specimens, one each from two separate rounds.

The time sequence used in manufacture of 0.33 water cement ratio specimens was as follows:

Mix - 5 minutes, vibrator setting 80
Fill and stopper - 20 " , " " 50
Invert and vibrate - 2 " , " " 50
Stand - 23 " , " " off
Reinvert and vibrate - 2 " , " " 50
Stand - 8 " , " " off
Invert and vibrate - 2 " , " " 50
Stand - 8 " , " " off
Reinvert and vibrate - 2 " , " " 50
Remove nut, break stopper seal and immerse in lime water.

Sequence for other water cement ratios was similar.

Stripping Molds

Again by trial and error, the best time to strip the mold was found to be about 20 hours after casting. If stripping was attempted earlier, the specimens were too fragile to be handled. If stripping was delayed beyond about 24 hours specimens tended to develop circumferential cracks. As previously stated, the stripping was a delicate undertaking. It was found necessary first to remove the teflon core; second, to loosen the O-rings that were bound in by the paraffin used to seal the various joinings; third, to remove the end pieces; and fourth, to roll the O-rings off the outside plexiglass mold. To strip the plexiglass mold it was found necessary to mount the specimen on a small jig designed for the purpose and on which it was possible to keep the specimen itself under slight compression during the rest of the stripping process. The plexiglass was expanded by inserting a small rod full length into the longitudinal slit, and then this mold was slipped off. Specimens were labeled with a soft pencil and stored in lime water.

Cutting and Lapping

Toward the end of the 28 day curing period, specimens that would be loaded for creep tests were cut to six-inch lengths using a diamond saw in a wet process. The ends of the specimens were then lapped square and plane on a glass plate using fine abrasive powders, a wet process. For creep test specimens one inch of paste was cut from the top of the seven-inch casting to leave a six-inch test specimen. The middle four inch part was the gage length. Care was exercised to keep specimens wet during all sawing, lapping and gage-mounting operations. Compressive strength test specimens were two inches long, and two could be sawed from the middle four inches of a six-inch creep specimen. Compressive strength specimens were lapped in the same manner as creep specimens. Strength tests were made at appropriate ages on a Riehle machine, and the results are recorded in Table 4 in addition to other data.

Number of Test Specimens

A round of test specimens consisted of four specimens cast from a single batch at the same time. Ordinarily, five rounds cast on consecutive days were manufactured for each variation of water-cement ratio proposed to be tested. Each of four specimens from a single round was prepared for a different exposure, and duplicates were prepared from a second round. Thus, for each variation of water cement ratio, two specimens from separate rounds were subjected to each test exposure. Compressive strength specimens were from the other three rounds. A set for 28 day strength tests included six specimens.

Method of Strain Measurement

Selection of a System

It was decided, after investigating a number of methods of strain measurement, that an optical method would be most stable over long periods of time and would provide the desired accuracy. Electronic methods, including automatic recording types, were considered and found to be of insufficient sensitivity or simplicity to be suitable for this application. The order of accuracy sought was five to ten micro-inches per inch. A number of gages, including the Tuckerman gage, supposedly produced accuracies better than five micro-inches per inch but none of these gages was found well suited for application to multiple specimen testing. Gages were desired that would allow a mobile specimen. The system finally selected was a modification of one that had been worked out by Mr. G. E. Monfore of the Portland Cement Association (34). In the Monfore system, a linear traverse magnifying microscope is used to observe differential movements of a strain gage manufactured from stainless steel hypodermic needle tubing. A one mil wire in a circumferential groove was used to form the fiducial mark.

Microscope

The instrument adapted to this research is a portable bifilar linear traverse microscope* with range of 0.08 inches, drum calibration of 20 microinches, 50 magnification, and a working distance of 1.5 inches.

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*Gaertner Scientific Corporation, Chicago, Illinois

This microscope is seen in Figure 5. The microscope mount was modified by the addition of a non-measuring vertical adjustment to allow centering of the microscope field on the strain gage. The microscope was moved from gage to gage for the taking of data.

Strain Gage

The strain gage shown in various stages of assembly in Figure 3 consists of two sizes of telescoping stainless steel hypodermic needle tubing to carry the fiducial marks and studs for attachment to the specimens. The gage, as adapted to this research, became a periscope gage with the fiducial lines offset above the specimen to allow immersion of the specimen without immersion of the fiducial marks. Two diametrically opposite four-inch gage lengths were centered vertically on each specimen. Holes were drilled in the specimen with a twist drill and spaced with the use of a combination drilling and assembly jig, one half of which is shown in the center of Figure 3. Studs made from the smaller size tubing and tapered slightly by grinding were driven into the drilled holes to be held firmly by friction. In the assembly of the gage, both sleeves of large tubing were placed over the long piece of small tubing. The short sleeve was soldered at the top to the inside tube; the long sleeve was soldered at the bottom to the top stud; and the long inside tube was attached to the bottom stud. The fiducial gage marks were scribed around the ends in closest proximity of the two sleeves. Movement between the two studs was read as a linear displacement between the gage marks. Shortening of specimens produced an increase in distance between marks, an important feature in compression testing because the gap between

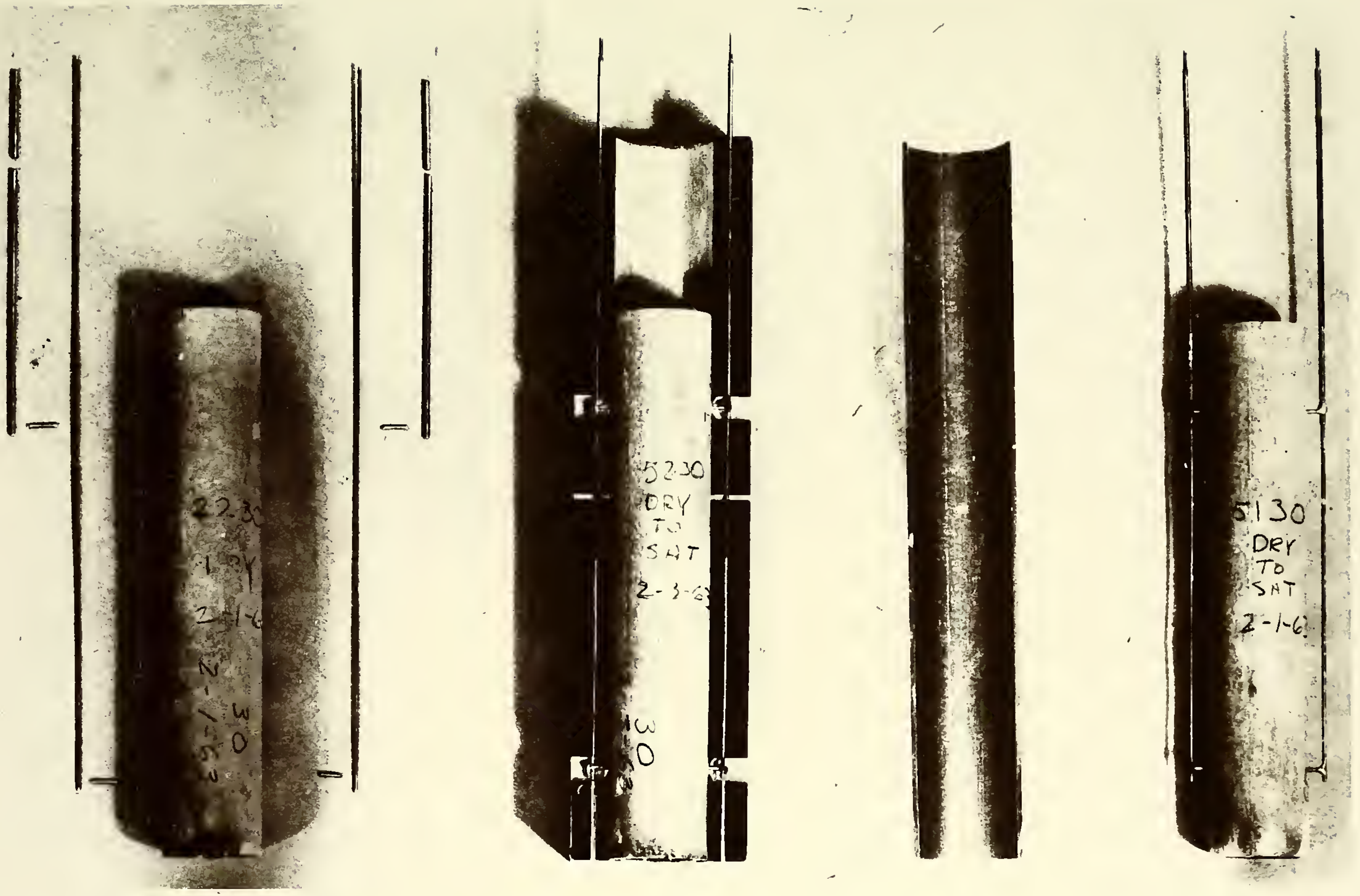

FIG. 3 STRAIN GAGE ASSEMBLY

sleeves widened upon application of load, and the gage could not be jammed by contact between the sleeve ends.

The fiducial mark or line was formed by cutting a narrow sharp groove around the tube on a jeweler's lathe. The cutting tool was a single edge safety razor blade which was barely touched to the tube surface. By side lighting the groove, a sharp black line was visible which could be intercepted between the bifilar cross hairs. Fixed sidelighting, visible across the top of Figure 5, was accomplished by installation of a single long fluorescent tube above and in front of the test rigs. At 50 magnification irregularities some times were observed in the fiducial marks, and in these cases, it was necessary to map the mark and to use the same segment for all determinations.

The annular space between telescoping gage parts was filled with silicone grease to prevent deposition of minerals and possible seizing up in immersed exposures.

Reading and Accuracy

In order to make one normal strain determination for a single specimen, it was necessary to read two separate gages that were mounted on opposite sides of the specimen. To observe the strain of a single gage, it was necessary to set the bifilar cross hairs upon one fiducial mark, record the reading, then traverse to the second mark and record that reading. The difference between these two readings was the total displacement between the gage marks at the time of reading. Displacement recorded for the gage at zero test age was subtracted from each later test age to yield the time deformation for the gage. The time deformations

for the two gages were added and converted to unit strain by dividing by the total gage length. The value thus obtained was recorded together with the temperature and the test age as one normal strain determination.

Data were recorded using an electric tape adding machine, computed as taken, and then transcribed into a bound data book.

For each normal strain determination four readings were required to record the data for eight inches of gage length, or an average of two inches of gage length per reading. The smallest microscope drum division was 20 micro inches, and it was possible to move the crosshairs off of the gage mark and to reset them to the nearest drum division. If the accuracy of setting per reading is divided by the inches of gage length per reading, a value of 10 micro inches per inch is obtained for the accuracy per strain determination. Actually, readings were estimated to the nearest half drum division and strain determinations were recorded to the nearest 5 micro inches per inch.

The maximum strain recorded during this investigation was 12,000 micro inches per inch and the minimum for a loaded specimen was 1600 micro inches per inch. A single determination accuracy of 10 micro-inches per inch seems reasonable for this range of recorded strains. For zero, final and other crucial determinations, values recorded were an average of six individual strain determinations per specimen.

For the various exposures, specimens were housed in individual environment chambers and the periscope gages extended up into vertical stacks made of 10 millimeter glass tubing as shown in Figures 4 and 5. All gage readings were taken with the microscope line of sight horizontal and thus perpendicular to the axis of the glass stack. Fiducial marks were also horizontal.

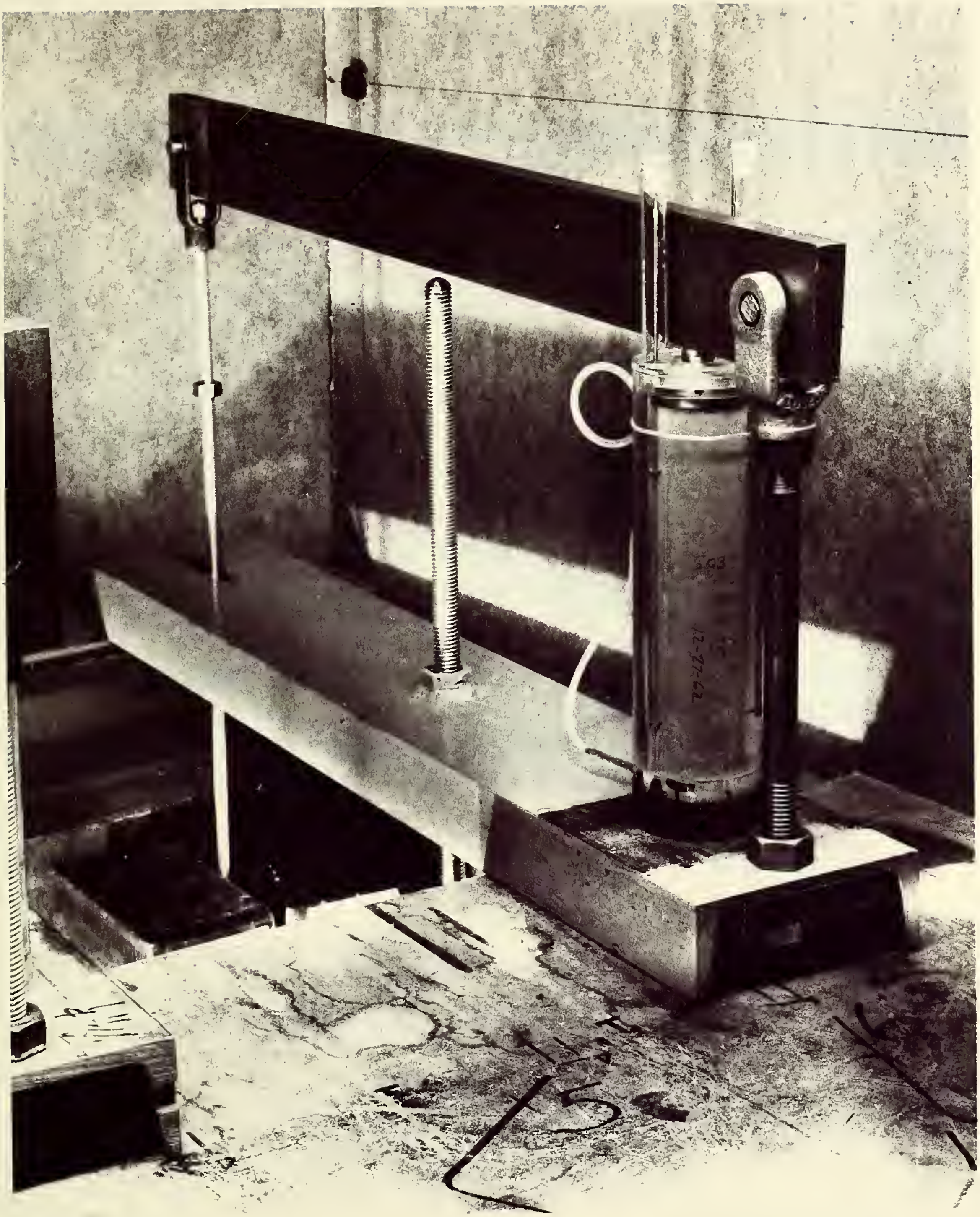

FIG. 4 LOADING RIG

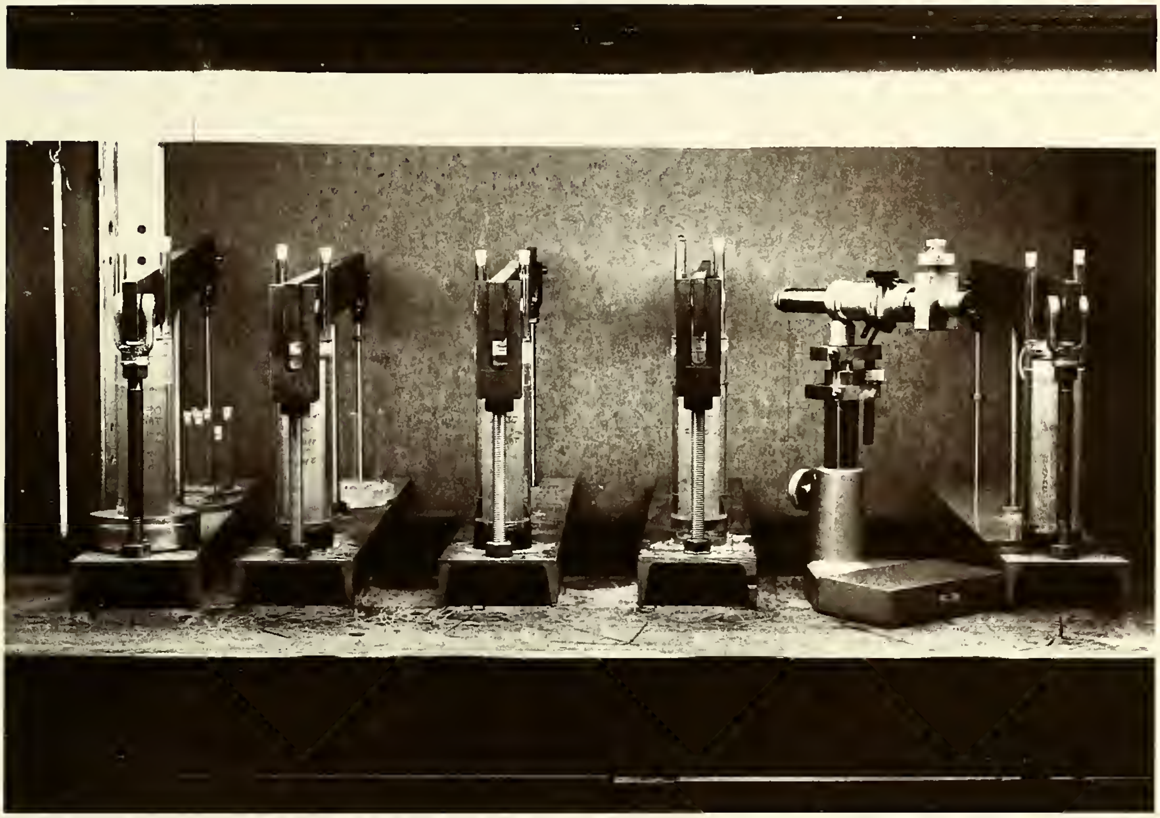

FIG. 5 TEMPERATURE CONTROL CHAMBER

Method of Loading

Loading was accomplished by application of dead weight multiplied in a 10 to 1 advantage lever type rig shown in Figure 4. Neville (35) reported the use of a similar, though spring loaded, rig. Load transfer to the top bearing block was through a half inch steel ball. The main reaction was a knife edge and the weight hanger assembly was pin connected. Load intensity could be varied by changing the dead weight on the weight hanger to produce stress in a specimen up to 10,000 psi.

Load could be applied to the specimen or removed in about 10 seconds by lowering or raising the lever bar on the threaded rod seen extending through the center of the base in Figure 4. A handle was attached to the other end of the rod for hand operation.

There were six loading rigs.

Testing Environments

The Laboratory

The laboratory was air-conditioned and maintained at approximately 25C. Humidity was not controlled but was observed and was in the range of 40-60 percent summer and winter.

Temperature Chamber

A temperature chamber was constructed wherein temperature was controlled to 25 ± 0.1 C. Cooling was continuous from air circulated by a blower directed over a cold water radiator. Heating was intermittent and was accomplished by thermocap* controlled use of two 300 watt electric

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*Niagara Electron Laboratories, Andover, N. Y.

light bulbs. Other heaters could have been used, but the lights doubled as visual indicators that the system was functioning, and specimens were shielded from direct radiation. Heating and cooling sources were located in a lower part of the chamber, while loading rigs, specimens and the microscope were in an upper part as shown in Figure 5. Weight hangers extended into the lower part of the chamber and the space was also used for storage of specimens under cure.

Individual Chambers

In order that the environment of each individual test specimen might be controlled, individual environment chambers were designed and constructed. One of these chambers that was used for either the saturated exposure or the dry exposure may be seen in Figure 4. For the saturated exposure the chamber was filled with saturated lime water solution, and for the dry exposure dry nitrogen was circulated through the chamber. For resaturation under vacuum a chamber was constructed in which the loading opening was sealed using O-rings. This chamber, while being pumped, would hold a vacuum of less than one-half millimeter of mercury. For dummies and rebound specimens there were multiple containers which could contain four individual specimens. The one for saturated specimens was a cylindrical container with places for four specimens. This container was not entirely satisfactory because of the possibility of disturbing the gages when removing the top to change individual specimens. As a result, it was found necessary to add all specimens to the container at one loading and to hold specimens until all specimens could be removed. This defect was overcome in the case of dry dummies and dry rebound

specimens by providing a cluster of four individual containers mounted on a single base. Individual specimens could be changed as required. These multiple specimen containers were mounted on turntables to allow specimens to be brought to reading position as desired. The turntables were installed in the cabinet between the 6 loading rigs to increase testing capacity by 16 dummies and rebound specimens.

Exposures

In general all specimens were cured 28 days immersed in saturated lime water solution. Lime water was used to avoid carbonation and resultant shrinkage that has been described by Verbeck (29).

Upon completion of curing, creep test specimens were placed for loading or as dummies in one of three basic exposures as follows:

1. Saturated - immersed in 25C lime water
2. Dry - immersed in 25C dry nitrogen
3. Dry then resaturated

The saturated exposure was actually a continuation of curing and was accomplished by filling the individual environment chamber with saturated lime water plus a small excess of free lime. Top and bottom bearing blocks in these environment chambers were perforated to allow free circulation of lime water or nitrogen in the case of the dry exposure between exterior region and interior cavity of the hollow test specimens.

The dry nitrogen exposure presented several problems of execution. It was necessary to oven dry specimens to constant weight at 110C and to keep them dry and free from carbonation at the 25C test temperature

for the period of the test. At the age at which saturated specimens were loaded companion specimens to be dried were removed from the saturated curing and a drying process was begun. This drying process consisted of vacuum drying for about six hours during which time approximately one half of the evaporable water was removed. Following vacuum drying the specimen was placed in the drying oven at 110C for a minimum of three days until all evaporable water had been removed. The required drying time was determined by weighing pilot specimens at intervals until constant weight was established for a period of at least 24 hours. Constant weight was reached for these pilot specimens in about 24 hours. The drying cycle was established as 72 hours minimum at 110C after initial vacuum drying. Upon completion of oven drying, specimens were removed to a desiccater, allowed to cool, were weighed and returned to the oven to be reheated. Reheated specimens were installed hot in the 25C nitrogen bath of the individual environment chambers. Dry specimens were allowed to reach temperature equilibrium in the nitrogen bath at which time zero gage determinations were made for the dry exposure. Saturated zero gage determinations had been made at the start of the drying process.

In drying of specimens it was found necessary to use a vacuum process for the initial portion of the drying to prevent cracking of the specimens. Saturated specimens placed directly in the oven from the water bath were found to crack longitudinally almost immediately. It was thought that perhaps this could be overcome by a period of air drying, but it was found that air-drying specimens also cracked in the same manner

soon after being placed into an air bath. This cracking was probably due to a differential rate of drying between the inside and outside surfaces of the specimen and possibly, in the case of the oven drying, to differential coefficients of expansion developing between various portions of the specimen due to differences in degree of saturation. Variation in thermal coefficient of expansion with variation in degree of saturation has been observed by Walker, Bloem and Mullen (36) and by others. Use of vacuum drying was successful in overcoming the cracking.

The success of the dry exposure depended upon maintaining a dry atmosphere to prevent water from getting to the test specimens. This was accomplished by immersing the specimens, in environment chambers, in a continuous flow dry nitrogen bath. Nitrogen entered one end of the system and was wasted at the other. Environment chambers were connected in series. The purpose of the nitrogen was two-fold. In addition to the elimination of water vapor, it was desired to exclude carbon dioxide to prevent possible carbonation of the specimens. To insure a dry nitrogen supply free of carbon dioxide, the nitrogen was put through a drying train starting from a 244 cubic foot commercial nitrogen cylinder. Nitrogen was passed through a diffusion nozzle into concentrated sulphuric acid, then through a trap filled with glass wool, and from there into a long cylindrical moisture trap of magnesium perchlorate. Initially, the nitrogen was fed from the magnesium perchlorate into the environment chambers, out the far end of the system through another magnesium perchlorate trap, and into a water bath where the outlet nozzle was immersed about one inch in the water. The purpose of the water bath was to give visual indication of the rate of flow of the nitrogen through the system. By observing the rate of nitrogen flow, it was possible to

detect leaks immediately and to proceed to their correction. In addition, the one-inch of water provided a back pressure on the system so that pressure of the system was higher than atmospheric pressure. In pilot tests it was found that some water was getting to the specimens, and they were gaining weight slightly in this nitrogen exposure. It was thought that the dried cement paste was a more powerful desiccant than the others being used and that water was getting to the paste for this reason. In an attempt to circumvent this effect a long cylindrical tube moisture trap of crushed dried cement paste was placed in the drying train, following the magnesium perchlorate, as an additional desiccant. The addition of the dried cement paste was not entirely successful, and specimens still gained slightly in weight. After completion of loading cycles, an amount of water was driven off by drying equivalent to the weight which had been gained. Because of the tendency for dried specimens to gain water, it was determined to transfer a specimen hot from oven to nitrogen bath to prevent water gain during transfer. Drying exposures were concluded with weight and strain determinations, followed by redrying and new weight and strain determinations.

Some of the dry specimens were resaturated while under load in an attempt to determine the extent of their rebound. Resaturation was accomplished in two ways. In the first case, resaturation was accomplished by taking the nitrogen outflow from the terminal water indicator and piping it into the environment chamber containing the specimen to be resaturated. ater was picked up by the nitrogen and transferred to the specimen. Length gain was a gradual process. This resaturation effort was continued until the specimen tended to reach an equilibrium in its

expansion process. At this time, the specimen was resaturated with water by filling the environment chamber from the bottom over a period of about 24 hours. In an attempt to avoid entrapment of air in the pores, water level was raised so there was always water rising up the specimen ahead of the water surface. This resaturation process was of several hundred hours duration and subsequent weighing indicated the resaturated weight was less than the original saturated surface dry weight.

In an attempt to shorten the resaturation process, and, also, to make resaturation as nearly complete as possible, it was decided to try a vacuum resaturation process. For this purpose the vacuum resaturation chamber mentioned previously was constructed. A specimen to be resaturated was removed from the oven cooled, weighed, reheated, and then transferred hot to the resaturation environment chamber. The chamber was sealed using O-rings, and the specimen was allowed to reach temperature equilibrium at which time zero dry gage length was determined. Load was applied and allowed to remain until equilibrium had been established in the strain time curve. The specimen was then evacuated under a pressure of less than a half millimeter mercury for approximately one hour. At the end of this time, water vapor was allowed to enter the chamber while the vacuum pumping was continued. Pumping was continued until water was boiling vigorously in the supply reservoir and at that time the pump intake was sealed and vapor pressure was allowed to rise to 15 millimeters of mercury. This took about a half hour. The chamber was pumped down again to a half millimeter mercury, and, while pumping was continued, water was admitted and allowed to fill the chamber. When the chamber was filled with water the pump was shut off and air was admitted

over the water reservoir, restoring atmospheric pressure to the system. Boiling stopped immediately and a rapid change of length began to take place in the specimen.

There was a fourth exposure which was used on a pilot basis. This was an autoclave exposure performed in accordance to ASTM Method C 151-60. The skelton results are indicated in Table 4. Specimens were autoclaved from a saturated condition and upon completion were dried or returned to a saturated environment, depending upon the exposure to be used in testing. The effect of the autoclaving was to reduce the strength of the specimens to approximately one third that of a normal cured 28-day specimen. Testing in this exposure was not pursued but remains an area of potential investigation.

Outline of Tests

Standards

ASTM methods of test were used where applicable.

Test Specimens

Creep test specimens and dummies were 6 inch long hollow cylinders having cross section area of 0.301 square inches. These were prepared from 7 inch long castings by cutting and lapping. Measurements were made over the middle 4 inches on two gage lines placed diametrically opposite on each cylinder. It is believed that end effects were eliminated as a variable by placing the reference studs approximately one specimen diameter from each end.

Compressive strength test specimens were cut two each, 2 inches long,

from the middle 4 inches of the 6 inch specimen, lapped for bearing and tested at appropriate ages. 28 day tests were averages of a minimum of 6 such specimens.

Specimens for density and evaporable and non evaporable water determinations were cut into one inch segments from 6 inch specimens as indicated in Figure 2. Determinations of these properties were made for initial and terminal specimen conditions for each exposure.

Four Variations in Water Cement Ratio

Water cement ratios by weight of 0.30, 0.33, 0.40, and 0.45 were selected to represent a range of gel pore and capillary void conditions. At maximum hydration, 0.30 water cement ratio paste should contain un hydrated cement and saturated gel; 0.33 paste should contain more saturated gel and less un hydrated cement; 0.40 paste should be completely hydrated with few capillary voids, if any; and 0.45 paste in addition to complete hydration should contain capillary voids.

In the presence of excess water, 0.2345 grams of water per gram of cement was required for complete hydration of the cement used in this investigation. However, it was not anticipated that complete hydration of the test specimens would be attained during the progress of the investigation, if at all.

Three Basic Exposures

A saturated exposure was selected to evaluate creep in the absence of drying shrinkage.

The oven dry exposure was intended to evaluate creep after completion of drying shrinkage and in the absence of evaporable water, a test of the

seepage theory.

The resaturation exposures were chosen to observe, if possible, an upper limit on creep of saturated specimens for a given stress level.

A fourth exposure, autoclaving, was used on a pilot basis only.

Type and Intensity of Loading

Specimens were loaded axially in compression at from 0.33 to 0.40 of 28 day compressive strength.

Type and Frequency of Observations

Weighings. Saturated surface dry weights were determined for all specimens to be dried. Oven dry weights from drying at 110C were obtained upon completion of drying. Weights for dry specimens were determined at end of the test exposure. Specimens were then redried at 110C and re-weighed. Weighings were performed on an analytical balance* and were recorded to the nearest 0.001 grams.

Densities. Wet densities were obtained by calculation from weighings in air and immersed of saturated surface dry specimens. Dry densities were obtained by weighing oven dry specimens and calculating the density in terms of the saturated surface dry volume, thus ignoring volume shrinkage due to drying. Weighings were made using the analytical balance.

Density values were obtained at the beginning and end of each exposure for each inch of height of the test specimen. This was accomplished by sawing density test specimens into the one inch segments

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*Christian Becker, Inc., New York, N. Y.

indicated in Figure 2. Tests were made in duplicate at the beginning and end of each exposure.

Evaporable Water. Evaporable water determinations were made by drying the density specimens. Evaporable water was computed as the difference between the saturated surface dry and oven dry weights. Evaporable water determinations were made for all oven dried creep specimens and dummies.

Non Evaporable Water. Non evaporable water contents were obtained on the middle four inches of density specimens by ignition to constant weight of a finely crushed sample. Two determinations were made for each of the four one inch middle segments from a single specimen. Duplicate specimens were tested. Non evaporable water values were recorded as grams per gram of ignited sample. These values were used to compute degree of hydration of the specimen at time of test.

Strain. Test age was computed from the instant of loading for creep specimens. Dummy control specimens were counted the same age as their loaded companions. Test age was recorded in hours. Zero strain determinations were taken within a half hour before load application. It was not possible to obtain an instantaneous strain value upon loading. It was possible, however, to obtain a 0.017 hour (1 minute) reading, and this was counted as zero for computing instantaneous elastic strain. Subsequent readings were taken at 0.083, 0.167, 0.25, 0.33, 0.417, 0.50, 0.67, and 0.83 hours test age. Also, readings were taken at 1.0, 1.5, 2.0, and 3.0 hours. Thereafter, strain observations were made at intervals varying from 4 to 12 hours depending upon the creep rate. The same sequence of observations was followed upon

removal of load application, except that after 100 hours of rebound, the interval between observations was increased to 24 hours for many specimens.

Summary

An outline of the tests showing water cement ratios, exposures, number of specimens tested, age of loading, and intensity and duration of loading is given in Table 3.

TABLE 3

OUTLINE OF TESTS

W/C	Number Specimens Tested	28D Strength psi	Test Loading psi	Loading Age Days	Load Duration Hours	Rebound Duration Hours	Exposure
0.30	2	17820	3500	19	1300	475	Sat.
	2	"	0	19	1300	100	Sat.
	1	"	3500	19[a]	1200	625	Dry
	1	"	3500	19	1200	4400	Resat.
0.45	2	8440	3500	56	1240	1010	Sat.
	1	"	3500	56	500	1625	Dry
	1	"	0	56	500	1625	Dry Dummy
	1	3240	1300	Autoclaved	460	130	Sat.
	1	"	1300	Autoclaved	420	90	Dry
0.30	2	17820	6000	29	800	800	Sat.
	2[b]	"	6000	29	100	190	Dry
	2	"	0	29	100	190	Dry Dummy
	2	"	6000	29	35	665	Vac. Resat.
	1[b]	"	0	29	0[b]	490	Vac. Resat.
	2	"	6000	51	360	370	Sat.
0.33	2	15560	5825	29	875	875	Sat.
	2	"	5825	29	200	410	Dry
	2	"	0	29	200	410	Dry Dummy
	1	"	5825	29	505	880	Resat.
0.40	2	10800	4300	29	875	690	Sat.
	1	"	4300	29	400	690	Dry
	1	"	0	29	400	690	Dry Dummy
0.45	2	8440	3370	29	800	800	Sat.
	2	"	3370	29	100	186	Dry
	2	"	0	29	100	186	Dry Dummy
	1	"	3370	29	490	-	Vac. Resat.

[a] Represents age drying begun for all dry specimens

[b's] One of these specimens resaturated after unloading and redrying.

Data

Cement

Characteristics of cement are presented in Table 1, and have been commented upon previously in the text on page 14.

Paste Density

Average paste density and variation of density with height for test specimens are presented according to water cement ratio in Table 2 and Figure 2. Methods for obtaining and computing these values have been commented upon beginning on page 40.

Compressive Strength, Non Evaporable Water and Percent Hydration of Test Specimens

Compressive Strength. The 28-day compressive strengths for the four basic water cement ratios used are presented in Table 4. Values are averages of a minimum of 6 of the compressive strength specimens described on page 38.

Non-Evaporable Water. Data for non evaporable water content of paste are presented in Table 4, and were obtained by igniting finely crushed samples of oven dried paste to constant weight in platinum crucibles. Non evaporable water was computed in grams of water per gram of ignited sample. These determinations were performed on the specimens that were used in the actual exposures.

A basic assumption, seemingly reasonable, was made that hydration of the dry pastes ceased upon drying, and, therefore, the non evaporable water content of the dry pastes was constant throughout the tests. It was further assumed that the non evaporable water content of the dry paste was also the non evaporable water content of the

TABLE 4

COMPRESSIVE STRENGTH, NON EVAPORABLE WATER, AND PERCENT HYDRATION OF TEST SPECIMENS

W/C by Wt.	Test Exposure	28D Compr. Stress psi	INITIAL			FINAL		
			Age Days	Non[a] Evap. Water g/g	Hydration Percent	Age Days	Non[a] Evap. Water g/g	Hydration Percent
9.00	Agitate	-	0	0	0	425	.2345	100
0.30	Sat.	17820	29	.1510	64.4	67	.1728	73.8
	Dry	"	29	.1510	64.4	29[b]	.1510	64.4
0.33	Sat.	15560	29	.1651	70.4	83	.1790	76.3
	Dry	"	29	.1651	70.4	29	.1651	70.4
0.40	Sat.	10800	29	.1784	76.1	96	.1935	82.5
	Dry	"	29	.1784	76.1	29	.1784	76.1
0.45	Sat.	8440	29	.1389	80.3	167	.2022	86.3
	Dry	"	29	.1889	80.3	29	.1889	80.3

[a] Non Evaporable water is computed as grams per gramof ignited weight

[b] Assumption is made that no hydration occurs beyond 29D as evaporable water has been removed -- See Table (7) for wt. change of dry specimens over duration of test cycle.

companion saturated specimens at the start of loading. These determinations were made only upon the segments of the middle 4 inch gage length section of the specimens.

Percent of Hydration. Values for percent of hydration at beginning and end of tests are shown for the various exposures and water cement ratios in Table 4. One hundred percent hydration was computed on the basis of .2345 grams of non evaporable water per gram of ignited sample weight for a sample of the cement hydrated for 425 days in an excess of water and continuously aggitated. Other values were computed in comparison to this value on the assumption that degree of hydration is proportional to the non evaporable water content.

Absolute and Bulk Volumes

Values for volumes of unhydrated cement, hydrated cement, gel pores and capillary pores are shown in Table 5 for various stages of hydration of the hardened cement pastes and have been calculated from data contained in Tables 1, 2 and 4.

For any degree of hydration, a hardened portland cement paste may contain unhydrated cement, hydrated cement, gel pores, and capillary pores or voids. In a closed system, gel pores will be saturated and capillary pores, if present, will be full, partially full or even vacant. In any event, if capillary pores are vacant or absent, hydration will have ceased, as hydration cannot take place within the confines of gel pores according to Powers (37, 38), L'Hermite (9), and Czerin (39). Thus, gel pores in a closed system will remain saturated.

In an open system, free to draw in additional water, capillary

TABLE 5. ABSOLUTE VOLUMES FOR HARDENED PORTLAND CEMENT PASTE COMPONENTS

W/C by wt.	Hydration percent	Age days	Vol. as Percent of Fresh Paste Volume				
			Unhyd. Cement	Hydrated Cement	gel	gel pores	Capillary pores
0.30	0	0	51.4	0	0	0	48.6
	64.4	29	18.0	53.0	74.0	21.0	8.0
	73.8	67	13.5	61.0	84.5	23.5	2.0
	100[a]	--	0	82.5	114.7[b]	17.5	0
0.33	0	0	49.1	0	0	0	50.9
	70.4	29	14.5	55.0	76.5	21.5	9.0
	76.3	83	12.0	59.5	83.0	23.5	5.0
	100[a]	--	0	78.0	108.5[b]	22.0	0
0.40	0	0	44.3	0	0	0	55.7
	76.1	29	10.5	54.0	75.5	21.5	14.0
	82.5	96	6.5	59.0	82.0	22.5	11.5
	100	--	0	71.2	99.0	27.8	1.0
0.45	0	0	41.4	0	0	0	58.6
	80.3	29	8.0	53.5	74.5	21.0	17.5
	86.3	167	5.5	57.5	79.0	21.5	15.5
	100	--	0	66.5	92.5	22.0	7.5

[a] Unattainable if value for gel volume exceeds 100 percent.

[b] Values in excess of 100 percent unattainable.

voids will remain saturated as long as they continue to exist. If capillaries become filled with reaction products, only gel pores will remain and hydration will cease even though all cement may not be hydrated. The gel is a bulk phase which contains hydrated cement and gel pores.

The effect of hydration of cement is an increase in solid reaction product by the addition of chemically combined water. There is, however, a net reduction in absolute volume due to a reduction in volume of the combined water. The exact value of this reduced volume is not agreed upon, but it is estimated variously to be between 0.74 and 0.87 of the original volume of non evaporable water. A qualified choice of 0.82 was indicated by Powers (38) who stated that the state of the subject, on the whole, was unsatisfactory. The 0.82 value is based upon the non-evaporable water determined according to a method described by Copeland and Hayes (40). Very little of this volume reduction has occurred at time of initial set, therefore, it is not reflected as a reduction of volume of the overall sample, but as an increase of volume of internal voids. In a closed system self desiccation may occur due to this internal volume reduction. A value of 0.82 has been used in the computations for Table 5.

Powers (38, 39), L'Hermite (9) and others have indicated that the minimum volume of gel pores will be 26 percent of the bulk gel volumes, and that 28 percent is a realistic working value. Further, it has been conceded that degree of hydration is approximately proportional to

$\frac{w_n}{w_n^{o}}$, the ratio of the non evaporable water for any degree of hydration to the non evaporable water required for complete hydration.

The volume of a sample of hardened paste may be stated as the sum of the absolute volumes of the components. Thus,

$$V_s = V_{uc} + V_{hc} + V_{gp} + V_{cp} , \qquad (1)$$

where

V_s = volume of sample,

V_{uc} = volume of unhydrated cement,

V_{hc} = volume of hydrated cement product,

V_{gp} = volume of gel pores,

and V_{cp} = volume of capillary pores or voids.

Also, it may be stated that,

V_c = initial cement volume,

V_g = volume of gel,

and V_n = reduced volume of w_n

Constants used were,

w_n^o = .2345 grams per gram

v_n = 0.82, the reduced volume factor,

$$\frac{V_{gp}}{V_g} = 0.28,$$

and

3.15 = specific gravity of cement.

Using these values, expressions for the components of V_s in equation (1) above became

$$V_{uc} = V_c \left(1 - \frac{w_n}{w_n^o} \right) \qquad (2),$$

$$V_{hc} = 1.605 V_c \frac{w_n}{w_n^o} \qquad (3),$$

$$V_{gp} = V_g - V_{hc} \qquad (4),$$

and

$$V_{cp} = V_s - (V_{uc} + V_g) \qquad (5),$$

Equation (4) may be rewritten as,

$$V_g = 0.28 V_g + V_{hc} ,$$

and this reduces to the more convenient form,

$$V_g = 1.39 V_{hc} \qquad (6).$$

The values for degree of hydration, $\frac{w_n}{w_n^o}$, have been obtained from Table 4 and computed volumes tabulated in Table 5. Corrections were not necessary for a reduction of volume due to bleeding of water, as the test specimen casting procedure was designed to eliminate bleeding.

Total Strain

The strain-time data for the basic exposures grouped according to water cement ratio, are presented in graphical form in Figures 6, 7, 8 and 9. Unless otherwise noted, each point shown represents the average strain for two individual specimens. Compressive strain is plotted on the ordinate as a positive quantity, although it actually represents a decrease in specimen length. Test age in hours is plotted on the abcissa to a logarithmic scale. Zero test age determinations and instantaneous elastic strain values have been plotted and labeled on the left ordinate with full knowledge that this is a violation of the use of the logarithmic scale. The left ordinate, in effect, is being used as a table for these values.

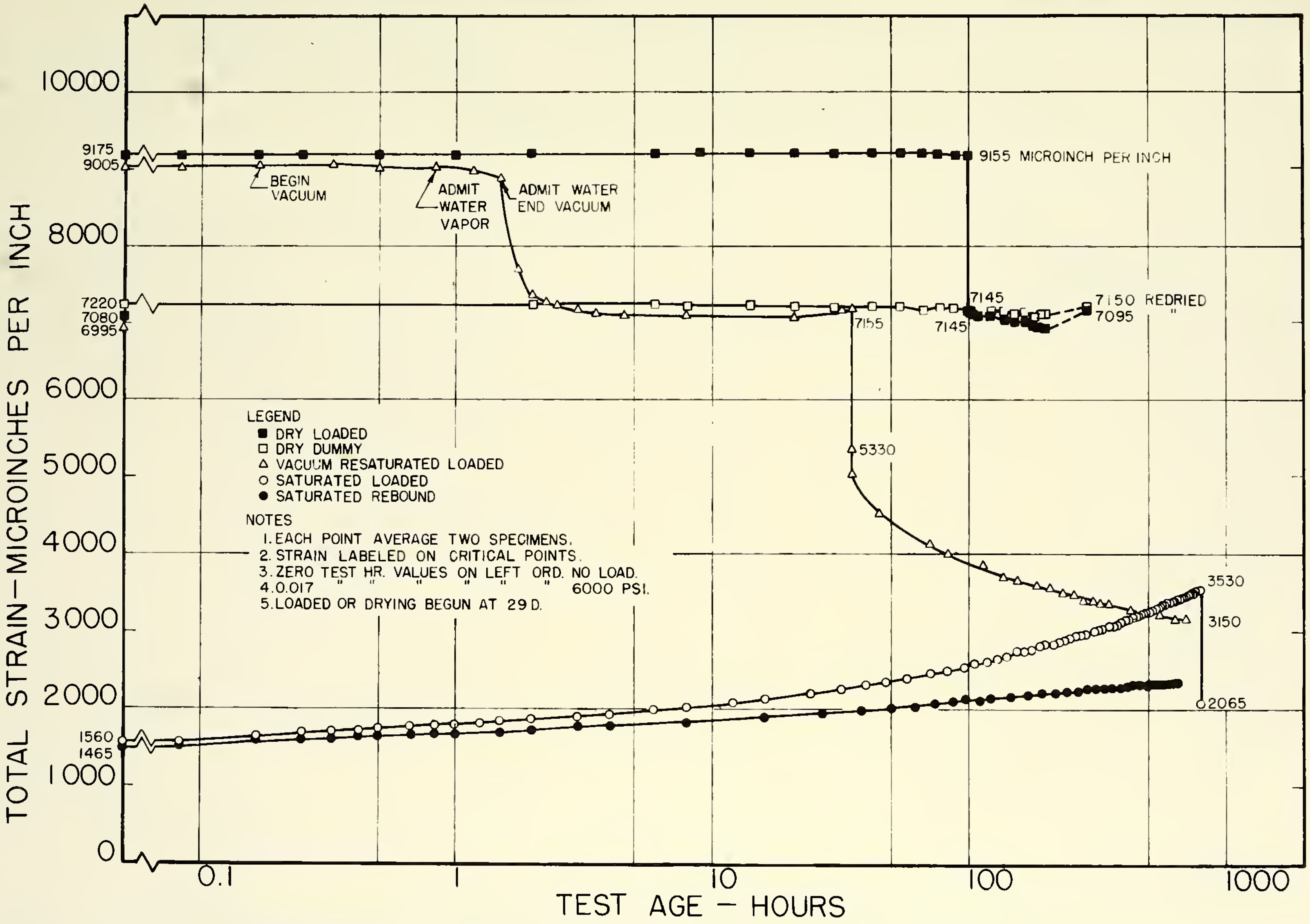

FIG. 6 STRAIN—TIME FOR 0.30 WATER CEMENT RATIO

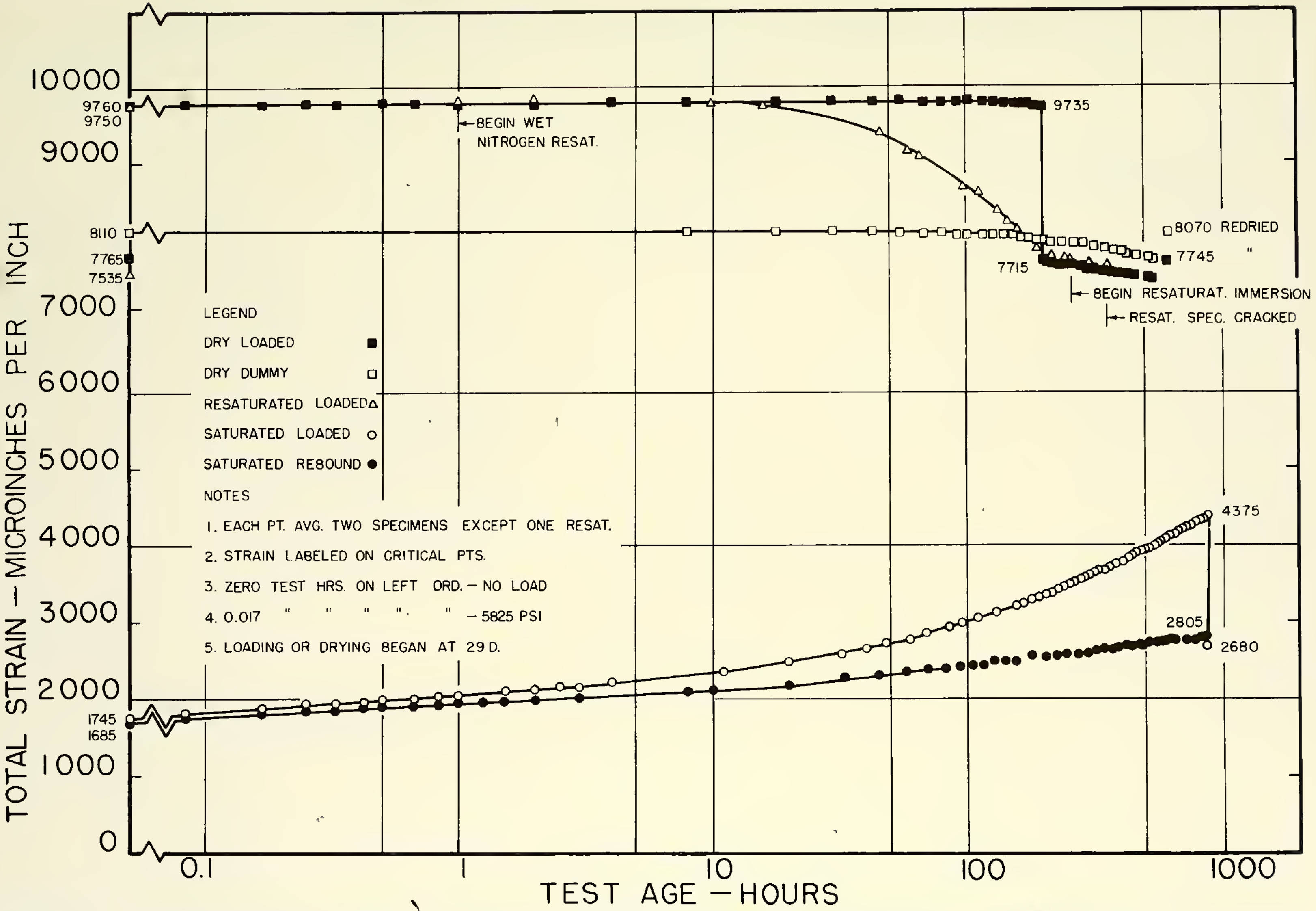

FIG. 7 STRAIN–TIME DATA FOR 0.33 WATER CEMENT RATIO

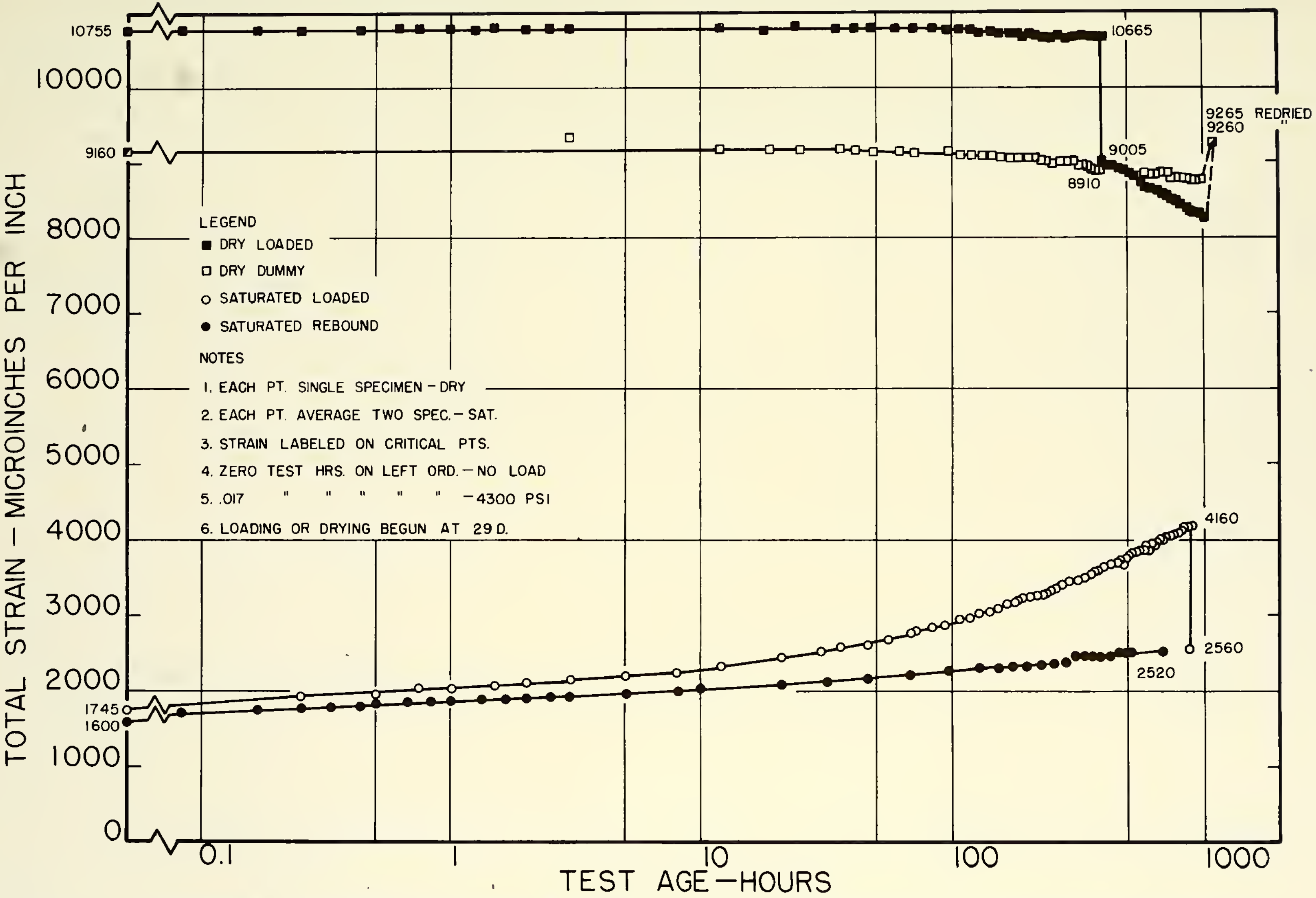

FIG. 8 STRAIN–TIME DATA FOR 0.40 WATER CEMENT RATIO

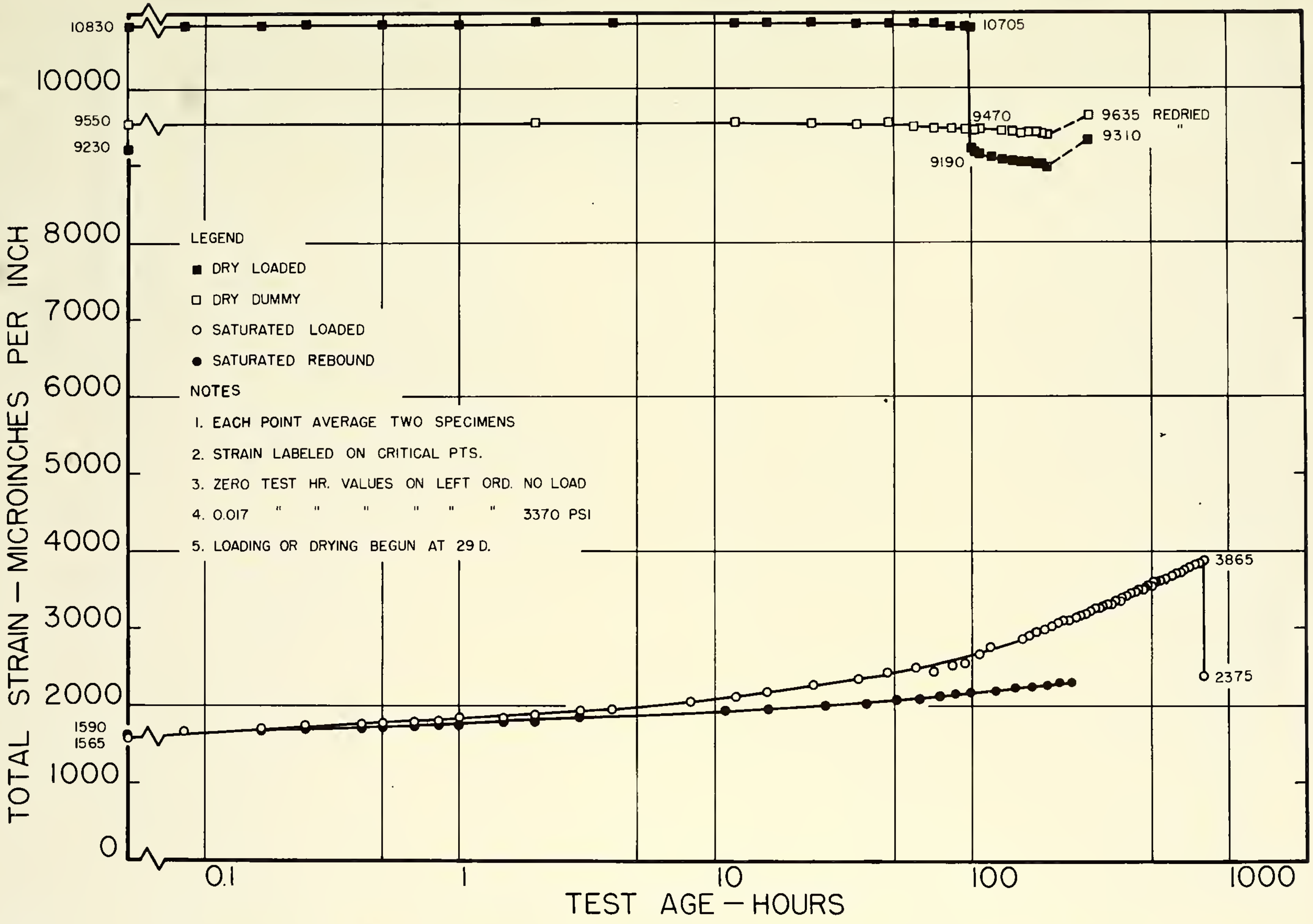

FIG. 9 STRAIN—TIME DATA FOR 0.45 WATER CEMENT RATIO

Rebound data for the dry and the resaturation exposures are plotted as a continuation of the loading curve.

For the saturated exposure, to improve comparison with load portion of the cycle, rebound data are plotted positively starting with the instant of unloading as zero test age. Positive values for plotting are obtained by subtracting rebound strain values from the load strain value recorded at the end of the loading portion of the test cycle.

In Figure 10, data for the loading portion of the saturated exposure are plotted as total strain per psi against test age for comparison of the time-strain behavior of the various water cement ratios. Values were obtained by dividing the total strain for each test age by the unit stress due to loading. Each point is the average of data for two specimens.

Elastic Strain

Instantaneous and delayed elastic strains are plotted by exposure and water cement ratio in Figure 11. Data are tabulated in Table 6. Instantaneous elastic strain is actually the 0.017 hour or 1 minute strain. Examination of the saturated load and rebound curves in Figures 6 through 9 will reveal that extrapolation toward zero to 0.001 or even 0.0001 hours would result in little change from the 0.017 hour value. A similar extrapolation for the dry exposure specimens would result in no change, indicating that, if there was any creep at the beginning of the dry exposures, equilibrium was reached before 0.017 hours.

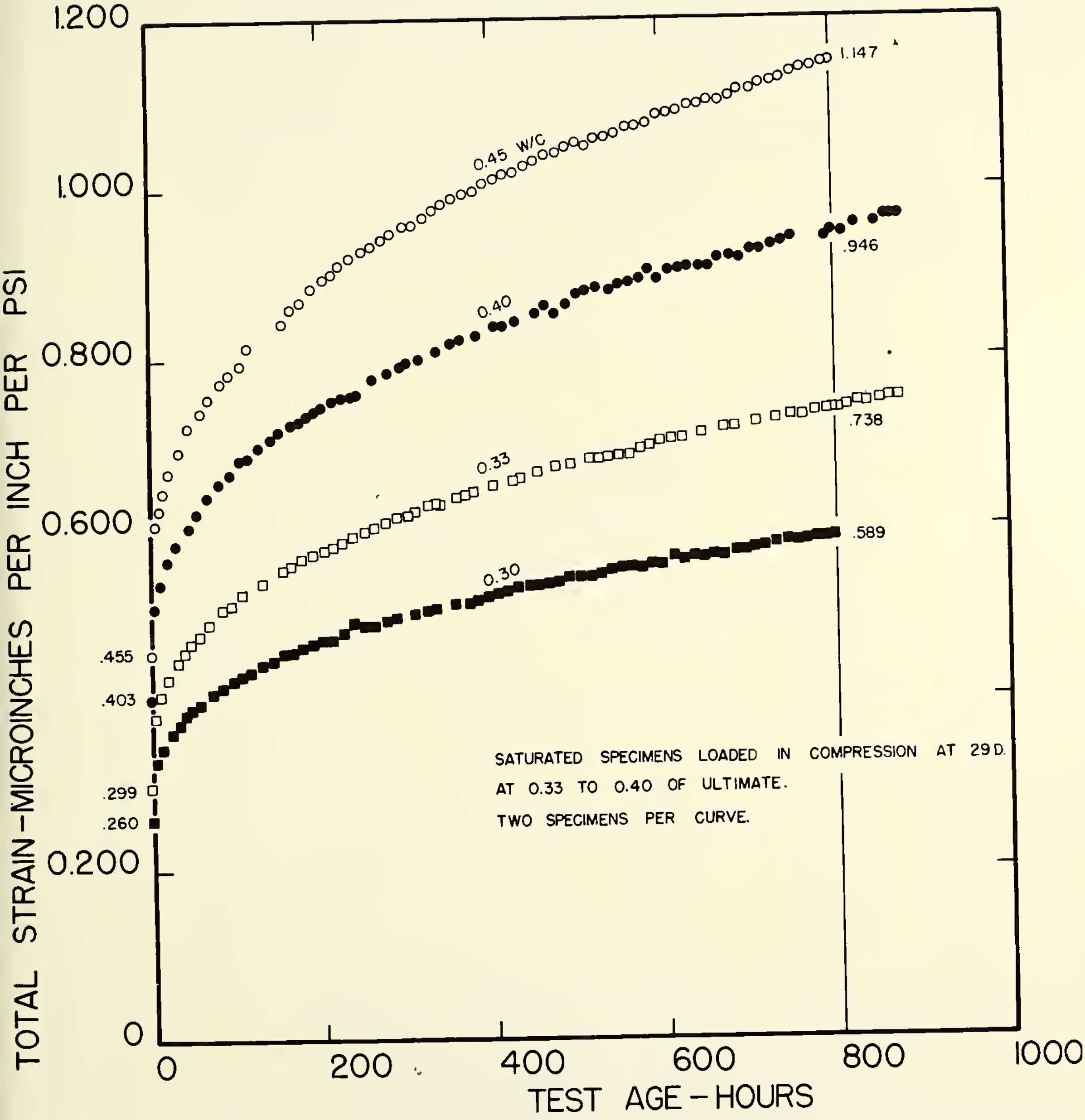

FIG. 10 EFFECT OF WATER CEMENT RATIO ON CREEP CHARACTERISTICS

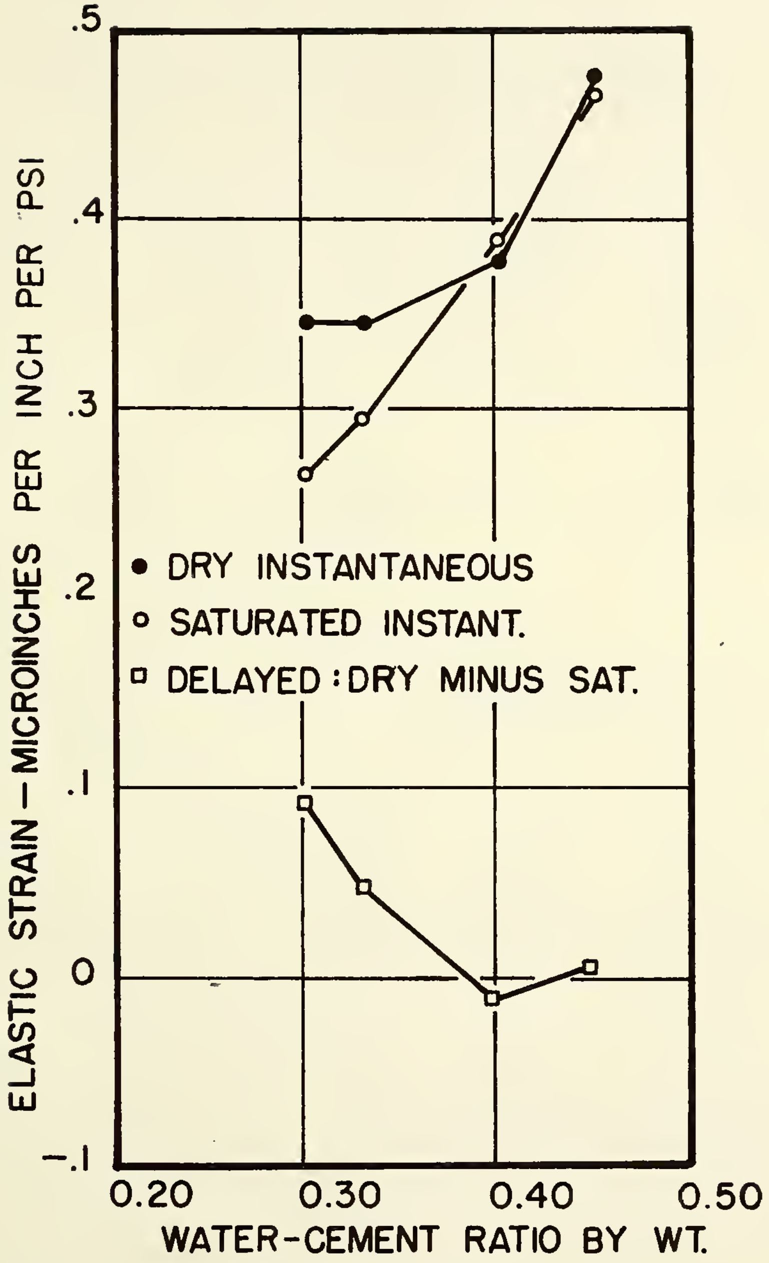

FIG. 11 INSTANTANEOUS AND DELAYED ELASTIC STRAIN

TABLE 6

INSTANTANEOUS AND DELAYED ELASTIC STRAIN

W/C by weight	Exposure	Test Load psi	ELASTIC STRAIN			
			Load	Unload	AVERAGE	
			micro-in/in	micro-in/in	micro-in/in	micro-in/in/psi
0.30	Dry	6000	2095	2010	2055	.3430
	Saturated	"	1560	1465	1515	.2625
Delayed elastic strain			535	545	540	.0905
0.33	Dry	5285	1995	1990	1995	.3430
	Saturated	"	1745	1685	1715	.2945
Delayed elastic strain			250	315	280	.0485
0.40	Dry	4300	1595	1660	1630	.379
	Saturated	"	1745	1600	1675	.389
Delayed elastic strain			-150	60	-45	-.010
0.45	Dry	3370	1600	1595	1600	.475
	Saturated	"	1565	1590	1580	.469
Delayed elastic strain			35	5	20	.006

Delayed elastic strain is computed as the difference between the instantaneous elastic strains of the dry and saturated specimens. Examination of the strain plots for the dry loaded specimens reveals that there was virtually no time deformation for this exposure, and, therefore, there should exist no additional delayed elastic strain component beyond that computed above.

Special Strain Effects

Scallop Effect. An apparent scallop effect or pattern has been recognized to a greater or lesser degree in all of the strain-time curves for individual saturated specimens. A typical example of this effect is shown in Figure 12. This effect tends to disappear when two specimens are averaged, and, therefore, does not show in the data presented in Figures 6 through 10.

It was felt that the appearance of this effect throughout the data was more than a coincidence connected with the normal scatter experienced in taking data, and, for that reason, the scallop effect is included here and will be discussed later in the text.

Length Changes in Oven Dry Pastes. It may be observed in Figures 6 through 9 that curves for dry specimens, loaded and dummy alike, at between 10 and 100 hours begin to exhibit an expansion, that shows up as a reduction in total strain. This expansion continues on into the rebound portion upon unloading and without comparison to the dummy would be construed to be creep recovery. At the end of the test, dry specimens and dummies were weighed, redried at 110C, reweighed, and total strain was determined. It will be noticed that,

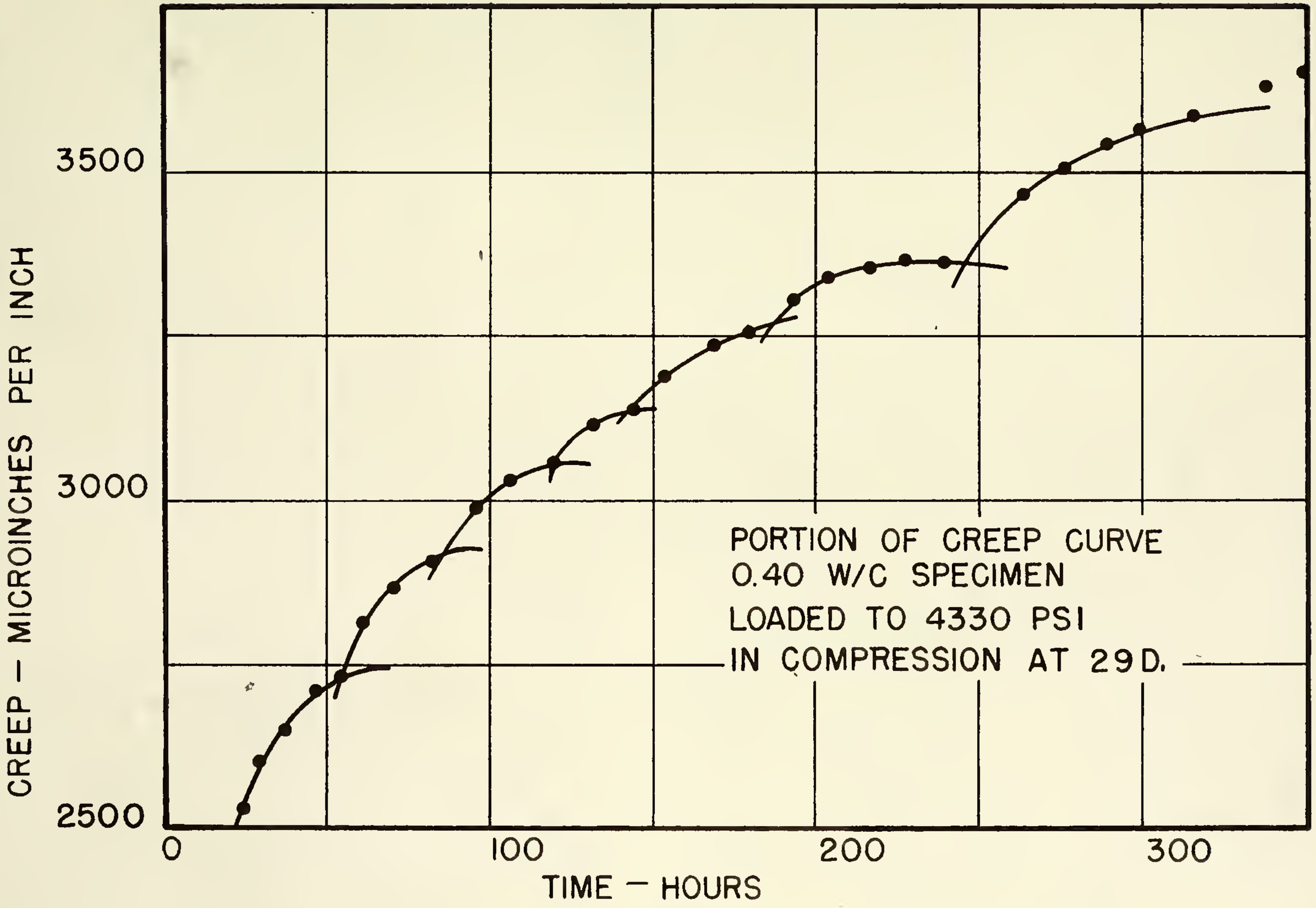

FIG. 12 TYPICAL SCALLOP EFFECT IN CREEP CURVE

in general, total strain for both load and dummy specimens was the same after redrying as it was after initial drying. Small weight changes were observed to accompany these small changes in strain. Strain and weight change values are shown in Table 7 and Figure 13.

Creep Reversal Effect. Examination of the vacuum resaturation curve in Figure 6 reveals expansion to a minimum total strain value at about 20 hours and then a reversal of direction of the curve toward increased total strain. This effect was noticed also in the preliminary tests on a 0.30 water cement ratio specimen where resaturation was by moist nitrogen and later immersion at atmospheric pressure. A portion of this curve is shown in Figure 14.

In Figure 7, it will be noted that the resaturation specimen cracked, before it was possible to observe whether creep reversal would occur.

An extreme case of creep reversal that occurred in the vacuum resaturation of a 0.45 water cement ratio specimen is shown in Figure 15.

Age at Loading. Effect of age at loading for 0.30 water cement ratio specimens loaded at three different ages is shown in Figure 16.

Creep Zones. Three apparently distinct zones were noted in extended loading of saturated specimens in pilot tests. An example is presented in Figure 17. This effect has been reported by Glucklich (41) and Reiner (15).

TABLE 7

LENGTH CHANGES FOR SMALL CHANGES IN EVAPORABLE WATER CONTENT OF OVEN DRIED PASTE

0.30 W/C		0.33 W/C		0.40 W/C		0.45 W/C	
weight change grams per gram of oven dry paste	length change micro-inches per inch	unit weight change	unit length change	unit weight change	unit length change	unit weight change	unit length change
.0051[a]	165	.0028	140	.0065	270	.0051	275
.0038	270	.0052	300	.0142	910	.0052	365
.0032	150	.0030	240	.0107	1010	.0049	280
.0019	105	.0051	490	.0128	410	.0054	330
.0047	120	.0057	520	.0096	515	.0034	235
.0038	150	.0047	270	-	-	.0036	420
.0025	100	.0030	210			.0013	95
.0015	65	.0041	250			.0025	90
-	-	.0020	145			-	-

[a] All values are for individual specimens, not averages.

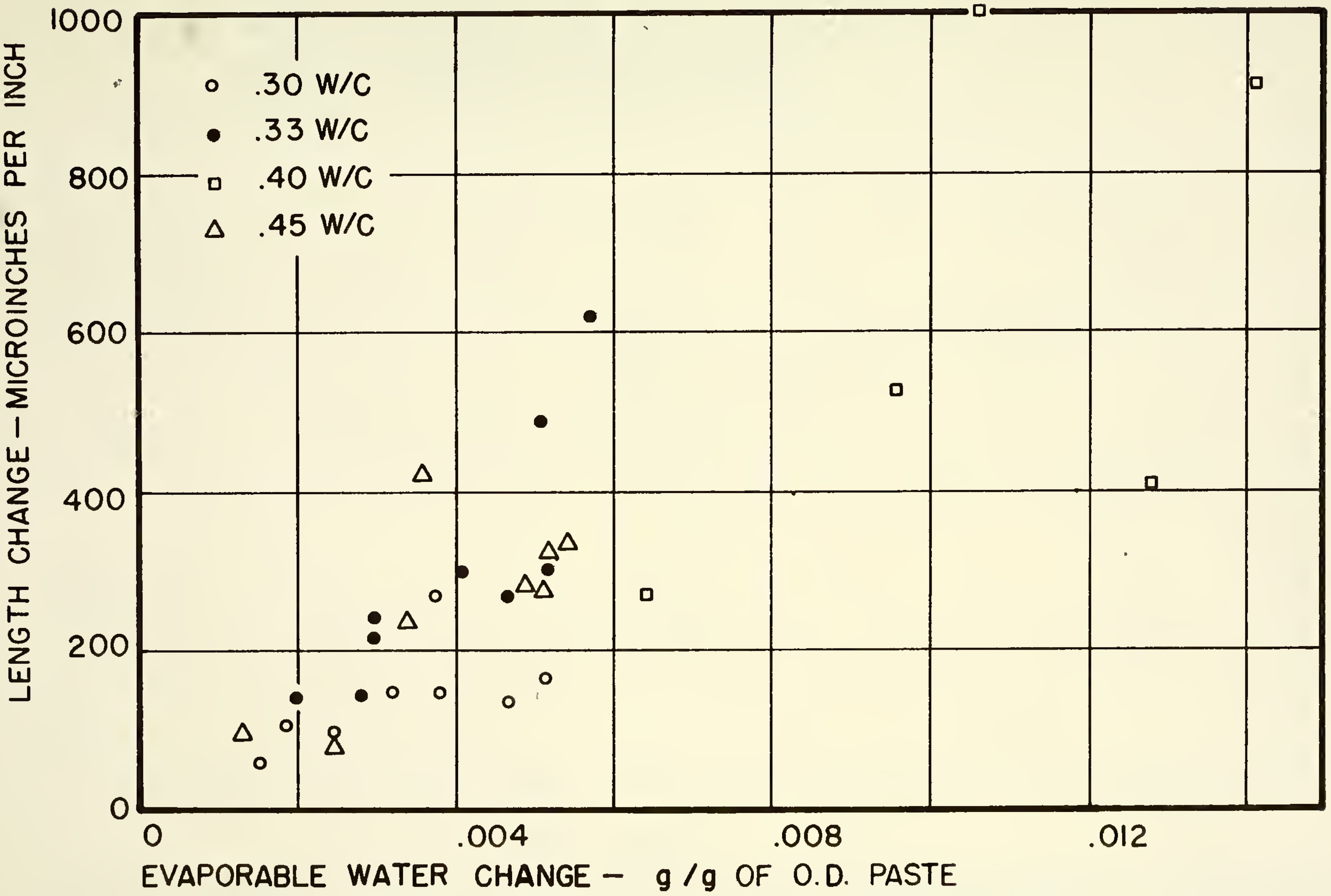

FIG. 13 NO LOAD LENGTH CHANGE IN OVEN DRY PASTES

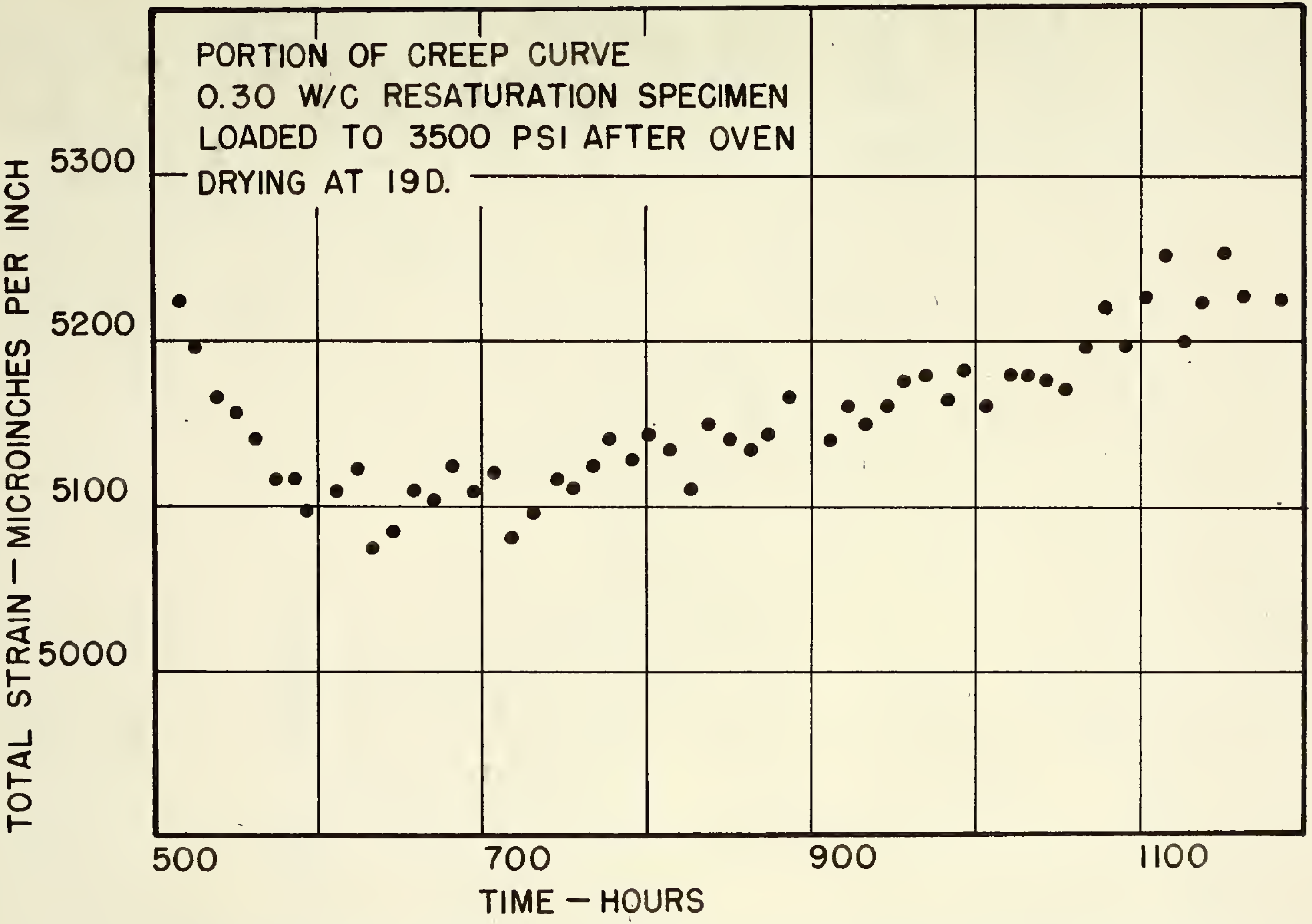

FIG. 14 CREEP REVERSAL EFFECT FOR RESATURATED SPECIMEN

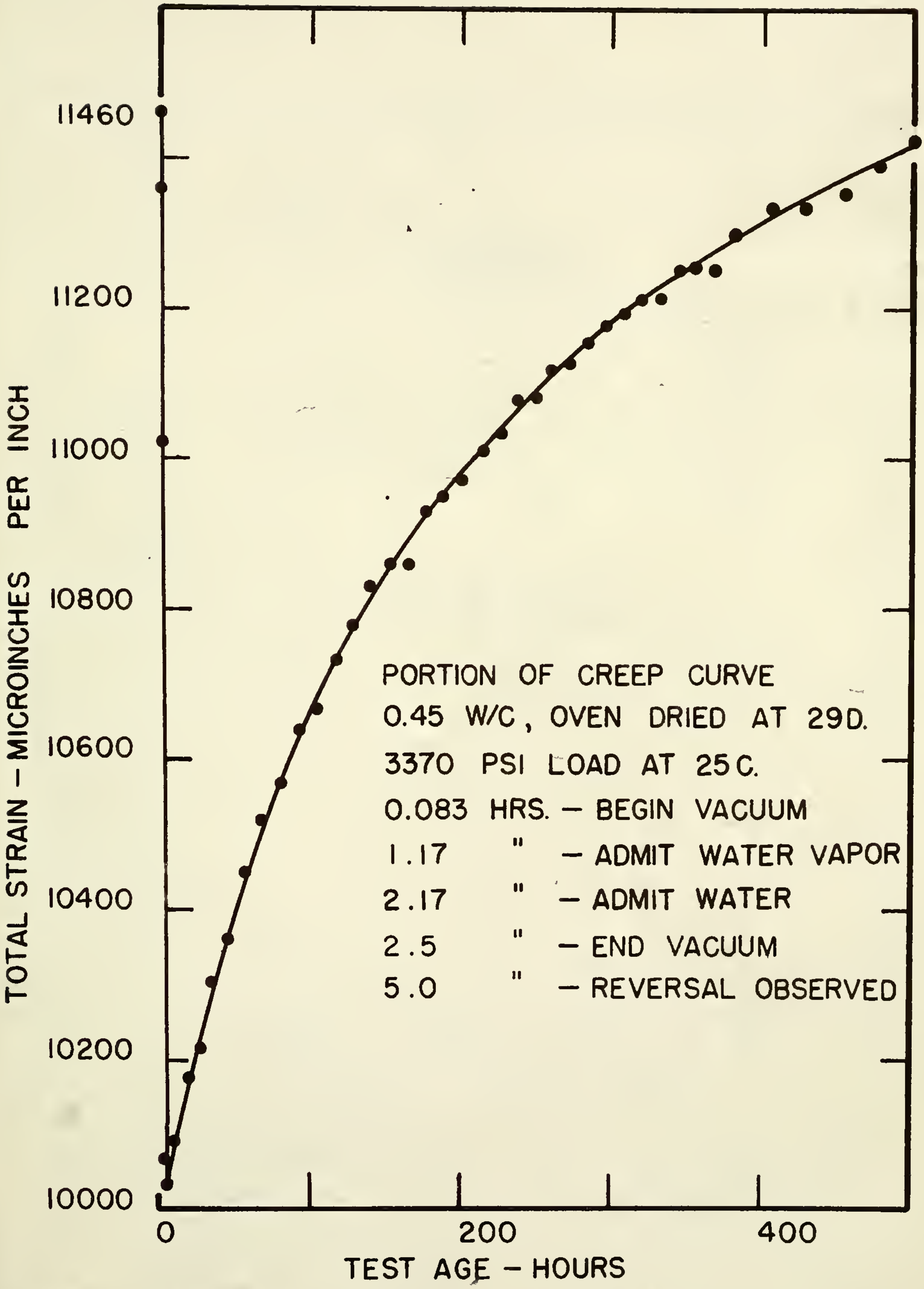

FIG. 15 CREEP REVERSAL – VACUUM RESATURATED

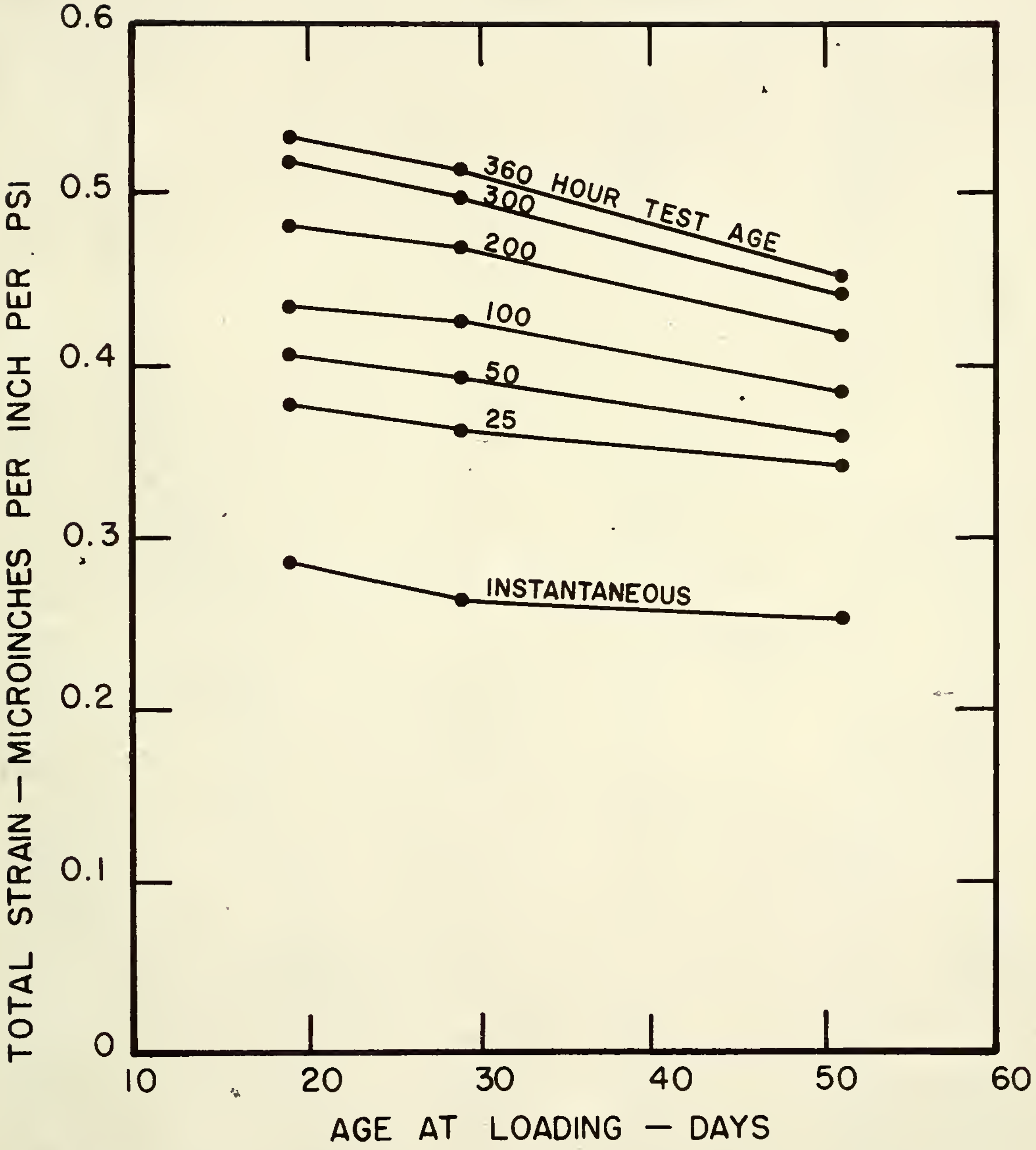

FIG. 16 EFFECT OF AGE AT LOADING ON CREEP OF 0.30 W/C SPECIMENS

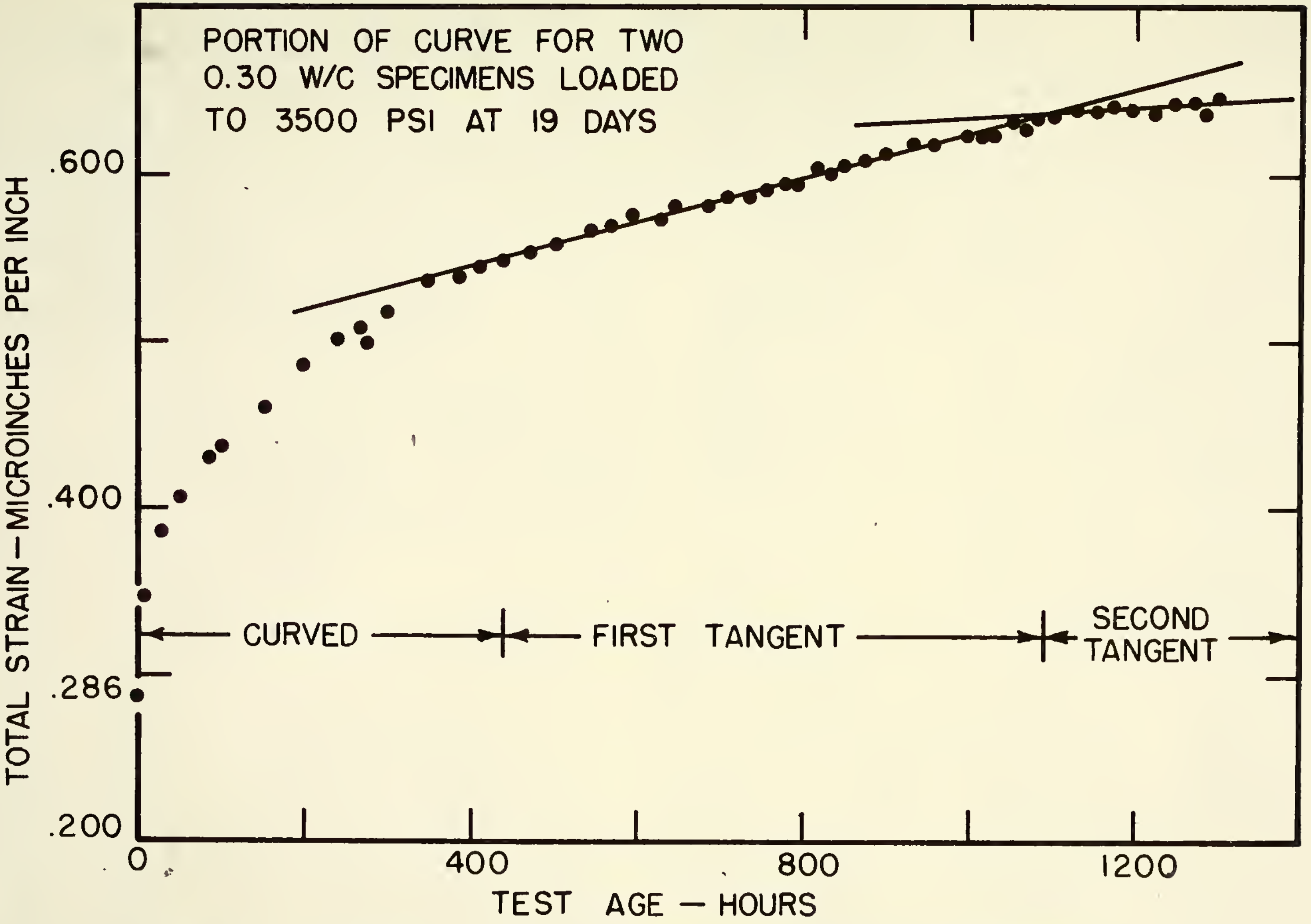

FIG. 17 CREEP ZONES FOR SATURATED EXPOSURE

DISCUSSION

Restatement of the Goals

The goals of this investigation, as stated originally on page 2, have been to evaluate the seepage and delayed elasticity theories of creep, the relation between creep and shrinkage, and the role of water in creep.

Testing for the evaluation of these creep properties of hardened portland cement paste has been carried out through the use of three environmental exposures, four water cement ratios, and two levels of stress.

Measurements

All of the measurements made during the course of this investigation, with the exception of the chemical analyses and visual evaluations, have been measurements of length, weight, volume, and temperature. It has been through control or deliberate variation of the factors influencing these measurements that an attempt has been made to accomplish the specific goals of this investigation.

Control of Non-Variables

A number of factors, both internal and external to the cement paste, are known to affect creep.

Temperature, method of specimen manufacture, specimen density, curing prior to testing, and carbonation were eliminated, as nearly

as possible, from influence upon the variation of measured values by the maintenance of constant values or procedures, or by prevention of occurrence in the case of carbonation. Control methods have been described earlier in the text.

Several factors, internal and interdependent, were less susceptible to control. These were associated with the rate of maturity of the hydration reaction and included the volumes of reaction product, of unhydrated cement, of uncombined water, and of gel pores and capillary pores or larger cavities. The approach to control was to provide, as nearly as possible, an identical environment and duration of pretest curing for all specimens. Exceptions were pilot tests where the duration of curing was a variable.

The degree of success of this approach is recorded in the values of Table 5, which shows maturity values from 65 to 80 percent at 29 days curing and from 74 to 86 percent at the completion of tests. From these determinations it was observed that maturity at a given age was a direct function of the water cement ratio for the four, 0.30, 0.33, 0.40, and 0.45, used in this investigation. Maturity may be a misleading measure in the case of the two lower water cement ratio pastes for which it may be seen from Table 5 that 100 percent maturity is unattainable since the gel-space ratio reaches unity, or the capillary cavities are exhausted before the supply of unhydrated cement is consumed. In these cases, relative maturity might be a more suitable measure. Relative maturity is defined here as the ratio of observed non-evaporable water to non-evaporable water required to produce a paste without capillaries, or, to completely hydrate the cement, which-

ever will occur first. For the cement in Table 1, both conditions coincide at a 0.39 water cement ratio. For example, it may be computed from the values of Table 5 or graphically from the plot of this data in Figure 18, that 100 percent relative maturity occurs at a maturity factor of 76 percent for a 0.30 water cement ratio. Thus, the 64.4 percent maturity value for the 0.30 water cement ratio at 29 days is equivalent to 84.8 percent relative maturity, and for the 0.33 water cement ratio at 29 days the values are 70.4 and 82.4 percent respectively.

In order to have actually controlled the maturity, it would have been necessary to have brought each paste to the same condition, preferably 100% relative maturity, before the start of testing and to have maintained this condition throughout the testing. For the saturated and resaturated exposures, this was a practical impossibility. The control exercised, then, was to render equal curing to all specimens before testing and to observe the maturity at the beginning and end of tests.

For the dry exposures, all specimens received equal curing before the start of drying on the 29th day. Maturity gain ceased with removal of water, and the specimens were thus controlled at constant, though not equal, values of maturity for the duration of tests.

Control of Variables

Deliberate variations were made of exposures, water-cement ratios, and stress levels. However, once established, it was attempted to control any variation as a constant condition. In other words, the variations, with one exception, were step like. The exception was

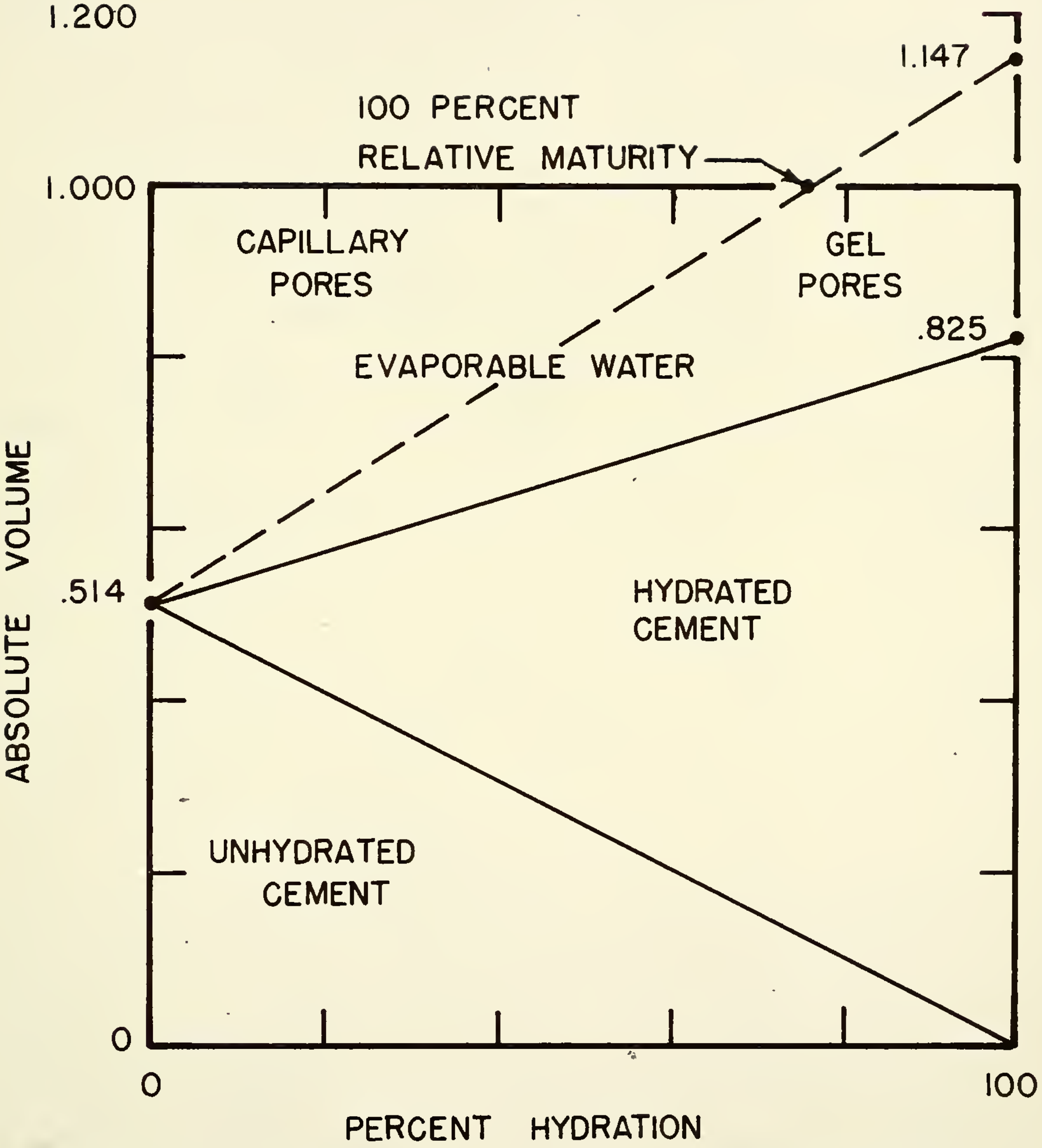

FIG. 18 VOLUME OF PASTE COMPONENTS – 0.30 WATER CEMENT RATIO

the resaturation exposure, where resaturation was, in part, a gradual variation from oven dry to saturated. The control of most of these variables was accomplished without undue complication.

Attainment of proper steps in water cement ratio for paste was accomplished in the specimen preparation as described earlier.

The saturated exposure was simply an extension of the curing procedure with the same control.

In the dry nitrogen exposure, oven-dried specimens gained weight in the order of 1 to 2 percent of the evaporable water lost during original drying. This weight gain was reversed upon redrying at the end of testing, indicating that the control of moisture though elaborate was not absolute.

Resaturation exposures were initiated either at atmospheric pressure or under vacuum. The question of control here becomes not one of efficiency, but one of efficacy with respect to specimen damage. It is feared that the process of resaturation may have been too severe or abrupt, and the process used is, perhaps, subject to question.

Qualitative Results

Owing to the limitation of equipment reuse, it was possible to test only 41 specimens exclusive of compressive strength tests. Generally, specimens were tested in duplicate, but in some cases there was only one. Taking of data was frequent and the scatter for individual curves was small, a condition that is reflected in the averages in the various plots.

Nevertheless, in some instances a variation was observed between duplicate specimens. In the case of saturated specimens it appeared as a variation of the initial elastic strain of as much as 5 percent

of the mean. The effect in plotting was observed as two identical curves separated from their mean by an almost constant value. A similar variation was observed between the individuals of a pair of dry specimens in the initial no load drying shrinkage strain. It is not known if these differences stem from differences in the specimens or from the gages. Conceivably, variation could be attributed to a disturbance of the gages in the dry specimens since the specimens are handled several times before final loading. Possibly, there could be slight differences of density, cross-sectional area, or curing even though these factors were closely controlled.

Creep in a Saturated State

Creep Zones

Creep curves for the saturated exposures are given in Figures 6-9 for the various water cement ratio pastes along with those of the other exposures, and, in Figure 10, in comparison with each other. In the creep curve for an extended test to 1300 hours that is plotted in Figure 17 there may be observed what are apparently three distinct zones to the curve. These zones are, one, an initial steeply curved zone that tapers into, two, a prolonged flatter zone that is roughly linear followed by an increased curvature and transition into, three, a second fairly linear zone. A zone effect has been noted and discussed by Glucklick (41) and Reiner (15) separately using the same data. Reiner cited the appearance of the third zone as evidence for a conclusion that creep is not viscous flow but mainly a delayed elasticity effect combined with non-recoverable creep. The data to which both of

these authors referred was that recorded by Glucklich (41) from loading tests of neat cement paste beams at low stresses in horizontal flexure. Mid-span deflections were measured on beams continuously loaded and on beams cyclically loaded and unloaded. Beams were sealed against moisture loss upon demolding by painting with a membrane coating. Their data, given in a plot similar to Figure 17, was that the first linear zone commenced at about two months and extended to 8 months. Thereafter, the second linear zone appeared and data were reported to 23 months. An interesting comparison can be made between these data and those in Figures 10 and 17 where the first tangent zone appears after about 400 hours and extends, in Figure 17, to about 1100 hours. Water cement ratios, curing, and exposure were similar, and differences were in the intensity and type of loading, and in the cross section of the specimen. Glucklich's beams were 0.86 inches square and 32 inches long compared to a wall thickness of 0.10 inches for the specimens reported here. This would indicate that there is a size or a load effect or both in the acceleration of creep rate. The ratio for the time to the end of the first tangent zone of this investigation to that for Glucklich's investigation is approximately 0.2. The foregoing is an example of the importance of the effect of specimen size in work of this nature.

The appearance of these three distinct zones in the creep-time curve point to the possible existence of three separate mechanisms of creep, the effects of which vary in magnitude with test age. Glucklich has attributed the early curvature to "secondary creep" that is non reversible, while "primary creep", an implied seepage or gel-water mechanism, was said to dominate the later portion of the curve.

Reiner (15) has stated that in earlier work of his on mortar and concrete that only the first of the two tangent zones was observed. The observation of this tangent led him and others to postulate that this was evidence of a viscous flow within the cement paste and that concrete was a "liquid" and not a solid. Reiner observed that the change of curvature when tests are extended, as in Glucklich's tests, is evidence that this original viscous theory was incorrect. Accordingly, he has stated that creep is mainly an elastic after-effect, and that his original concept was an error that was shared with others.

Neither Reiner nor Glucklich specifically mentions a "second tangent" zone as shown in Figure 17, but only a flattening of the slope to indicate that the first tangent zone is not truly linear. Probably, the second tangent zone is not linear either, and the transition from one zone to the other, as well as that from the curved to the first tangent zone, may indicate the ascendency of one creep mechanism and the decline of another.

Scallop Effect

Corroboration for the contention that more than one mechanism of creep may be active in the curved zone of the creep curve can be deduced from the appearance of a scallop pattern in the individual point pattern for single specimens. A typical scallop effect is most noticeable in the initial or curved zone and is illustrated in Figure 12. When point values for two specimens are averaged, this scallop effect tends to disappear. If there were a single mechanism, or two or more uniformly varying mechanisms at work, the point pattern would be random and

scallops could be plotted concave downward and upward with equal ease. Scallops were invariably plotted more easily concave downward, indicating an intermittent or cyclic creep variation.

If viscous flow alone is a mechanism of creep, it would be evidenced by a linear creep curve. Therefore, viscosity, if present, would not contribute to the scallop pattern. Seepage of gel water and the sort of delayed elasticity that is envisioned here will be inseparable from each other. Pure seepage or viscous flow of gel water should result in a linear creep curve just as would viscous flow of the "fluid" cement gel. But the combination with delayed elasticity, involving a transfer of load onto and a build up of stress in the solid skeleton, and a decrease of pressure in the water, should result in a logarithmic or hyperbolic curve. Micro fracture or discrete particle reorientation would logically tend to be irregular and step like in pattern when plotted.

Consider the application of load to a saturated specimen. An elastic deformation occurs instantly. The stress is carried in part by the solid gel skeleton and in part by the water phase. Initial time deformation rate is high as consolidation takes place due to expulsion of water from the gel pores, and the gel skeleton particles move together to occupy the space vacated by the water. Point to point particle contacts are established and stress in the solid phase increases at the expense of pressure in the water phase in the gel pores. In other words, a load transfer progressively takes place from the water phase of the gel to the solid phase. Some of the particles are therefore deformed elastically in what may be called a delayed elastic effect.

In time, the observed creep curve tends to flatten out, and a maximum or threshold value of inter-particle stress for the system, as oriented, is approached and exceeded. There then occurs a more or less precipitous reorientation of gel skeleton particles toward positions of greater stability. This reorientation is triggered by the fracture of some of the more highly stressed gel skeleton particles and proceeds rapidly as a readjustment that would appear as a highly accelerated deformation in the absence of the damping effect of the water. In wet specimens, however, the load is transferred to the water phase by this process. The result is a decrease in the strain rate and the appearance of a cusp in the creep curve.

When this reorientation occurs, the gel skeleton particles, relieved of stress, expand elastically reversing the delayed elasticity effect somewhat. A new cycle of seepage begins, and stress transfer back to the particles of the gel skeleton proceeds toward a new and higher threshold stress which may be exceeded as before. Reorientation is triggered and a new cusp appears in the creep curve. Repetition of this process results in the scallop effect. This process continues until there is established finally a threshold stress that is equal to or greater than the stress induced by the applied load. After this event, the seepage consolidation will continue until the gel pore pressure is dissipated, the gel skeleton carries the full applied load, and, the full delayed elastic deformation is developed.

The scallop effect, then, may be evidence of gel skeleton particle fracture and particle reorientation toward maximum stability, an intermittant mechanism, coupled with a seepage or gel water flow

consolidation mechanism. Delayed elastic deformation occurs, but this mechanism is postulated to be cyclic due to a transfer of stress back and forth between the water phase and the solid phase.

Saturated Dummies

No-load, saturated specimens or dummies were included as control specimens for each of the two loaded, saturated specimens reported in Figure 17. The average change after 1400 hours was -25 microinches per inch, and the average extreme variation during the 1400 hours was from + 40 to - 90 microinches per inch.

On the basis of this evidence saturated dummies were not included in the remaining tests. This is evidence that no mechanisms of deformation other than those induced by the application of load were acting.

Creep Recovery

Curves of creep recovery or rebound are plotted by water cement ratio in Figures 6 through 9. These data are plotted as positive quantities by using the final load strain as the zero datum and plotting the difference between this datum and the total strain recorded for each rebound determination. The zero test age for rebound has been taken as the final test age for the load cycle. This method of plotting does allow a comparison of the general shapes of the load and rebound curves, but caution must be exercised against a comparison of these curves for hour to hour correspondence. The origin in time for the two curves is different, and the mechanisms of creep recovery may be different from those of creep.

However, the shape of the two curves is different, the recovery

curve being the flatter of the two. The instantaneous elastic strain values are nearly the same with perhaps a tendency for the initial elastic deformation to be slightly greater than the rebound elastic recovery. This effect has been observed by others (6) and generally is attributed to a change in the modulus of elasticity through an increase in the maturity factors over the time of the load cycle. If the theory of seepage consolidation is valid, then the paste structure is denser and less permeable at the end of the loading phase through the action of consolidation. This effect is coupled with the increase in the maturity factor. A decrease of permeability would have the effect of increasing the time required for delayed elastic recovery. In the one minute that elapses between addition or removal of load and observation of strain some delayed elastic deformation must occur. If the rate of attainment of delayed elastic strain is larger upon loading than upon unloading, this would be reflected as a decrease in apparent instantaneous elastic recovery in comparison to the apparent instantaneous elastic deformation.

It will be noticed in Figures 6 through 9 that there is a gradual divergence between the load and rebound curves in a semi-log plot. Even though these data may not be comparable on an hour for hour basis, this divergence seems to imply that irrecoverable strain or permanent set is accumulated gradually. If true, this implication would tend to support the evaluation of the mechanism postulated to explain the scallop effect. As further supported, it may be stated that the scallop effect was observed only to a minor extent in the rebound curves, if at all.

One of the specimens for which data are reported in Figure 17 was continued in rebound for 4300 hours at which time recovery was still continuing at a practically constant rate. Residual strain for this one specimen was 450 micro inches per inch at 4288 hours, a recovery of two thirds of the time dependent strain.

At later ages the various saturated creep recovery curves in Figures 6 - 9 approach linearity on the semi-log plot. This implies a logarithmic function for this part of the creep curve.

Creep of Dry Specimens

Paste specimens that were oven dried at 110 C to constant weight and then loaded in compression exhibited no time dependent deformation due to load. Examination of the plots in Figures 6-9 indicates that there was a slight expansion during the progress of the tests. This expansion was determined to be due to inadvertent water gain, and it was reversed upon redrying. Expansion was generally proportional to the water gain. The data are plotted in Figure 15. It is reasonable to state that cement paste does not creep at all in the absence of evaporable water. Glucklich and Ishai (24) in torsion tests of dry cylindrical cement mortar specimens reported that no creep was observed after three days. Deformations up to three days were described by them as erratic and were not reported. The erratic behavior was attributed to cracking. Hrennikoff (25) in incremental loading and unloading tests of cement paste reported that dry paste exhibited little creep.

It may be seen from Table 6 that the elastic strains of dry specimens were almost completely reversible and, with one exception, were greater

than those for saturated specimens for the same load intensity. In the complete absence of creep for dry specimens, it must be assumed, either, that all of the "creep" has taken place in the shrinkage process, or, that creep cannot occur in the absence of water.

If all of the "creep" has taken place in the shrinkage process, then an upper bound, independent of applied load, has been found for the total time-dependent deformation. This important concept of an upper limit on time dependent deformation that is independent of load will be designated the absolute creep potential. The implication in this designation is broad. Regardless of the duration of loading, or the moisture condition of the paste, the total time dependent deformation, which excludes elastic deformation, will not exceed the drying shrinkage for the hardened portland cement paste determined at the time of loading. It has not been demonstrated, however, that the absolute creep potential will ever be achieved, and, indeed, there is some evidence that it may not be achieved; that will be discussed later in the text.

Delayed Elastic

In accord with the concept of absolute creep potential stated above, and the observation that instantaneous elastic strains of oven dry specimens are larger than those of saturated specimens, then it may be deduced that the delayed elastic strain is the difference between these two strain observations for comparison specimens. Values of the delayed elastic strain for the various water cement ratios are tabulated in Table 6 and plotted in Figure 11.

It will be noticed that the two higher water cement ratio pastes showed no appreciable delayed elastic strain. This may be due to a specimen size effect combined with the volume of capillary voids in the paste. The lower the volume of capillary voids, the higher the resistance will be to flow of expelled water, and therefore the greater will be the delay in the transfer of load from the water phase to the solid phase in a saturated system free to drain. There should logically be some value of voids in relation to the mean flow path such that dissipation of pore pressure will be very rapid and practically no delay of elastic response to load will be observed. An examination of the capillary void volumes in Table 5 reveals a significant difference in these volumes from the lowest to the highest water cement ratio.

The capillary pore volume for the 0.30 water cement ratio specimens was the lowest, and their delayed elastic deformation was the highest. For the two highest water cement ratios, the critical capillary void volume for the very rapid dissipation of pore pressure postulated above was probably exceeded and therefore, there was no observed delayed elastic response. An increase in the flow path, or a decrease in the volume of capillary voids or a combination of these two could result in the appearance of delayed elastic response in the higher water cement ratio pastes. This effect has not been attributed to the gel pore volumes, and it will be noticed in Table 5 that these volumes were approximately equal for all water cement ratios for the duration of tests.

Resaturation

Expansion Under Load

Data for loaded resaturated specimens are plotted in Figures 6 and 7 in comparison to the other exposures, and in Figures 14 and 15 to illustrate special effects. Supplying water, in the form of vapor added to the nitrogen, caused the specimens to be rewetted at atmospheric pressure and to expand. When the expansion slowed, the specimens were gradually immersed by flooding the individual chamber with water. A small amount of additional expansion occurred, quickly followed by a leveling of the creep curve, and, then, a reversal.

With regard to expansion, Powers and Brownyard (27) have stated,

> "Cement paste shrinks and swells as the cement gel loses or gains water. Swelling results when the surface forces of the solid phase are able to draw water into the narrow spaces between solid surfaces. ----
>
> "Shrinking results when water is withdrawn from the gel. It is probably due to the solid to solid attraction that tends to draw the solid surfaces together, though capillary tension and elastic behavior may also be involved.
>
> "By this theory, volume change is regarded as being the result of an unbalance of forces acting on the adsorbed water.----"

It seems reasonable to assume that the shrink and swell mechanism outlined above is as valid under load as it is when there is no externally applied load. The effect of the addition or superposition of external load would be to change the magnitude of the "unbalance of forces acting on the adsorbed water", and, consequently, the degree of force adjustment required to achieve an equilibrium.

For the case of resaturation of the loaded dry specimens, gel pores are filled, and the gel skeleton is expanded by the swelling pressure

until the stresses induced by the pressure in the gel pores reach equilibrium with the stresses induced by external loading. In the absence of the action of any mechanism of volume change other than swelling and external load, a condition of equilibrium will be reached, and the creep curve will become horizontal. The total strain will now consist of an elastic deformation and an unrecovered shrinkage.

The amount of unrecovered shrinkage will vary with the applied load and, for less than fully saturated specimens, with the humidity of the environment. The unrecovered shrinkage at equilibrium, plus the delayed elastic deformation, if any, is designated as the equilibrium creep potential. This is the maximum value of time-dependent deformation that will be obtained on loading a specimen. It is dependent on the load, and, for partially saturated specimens, on the humidity, i.e. on the swelling pressure. Its maximum value is the absolute creep potential that is obtained with no load and complete drying. These concepts are illustrated in Figure 19.

Creep Reversal

In the definition of equilibrium creep potential, a stated condition was that no other mechanism of volume change other than the swelling mechanism be acting. This may not always be the case. Creep reversal or a change of the slope of the creep curve from expansion to contraction after rewetting can be observed in Figures 6, 14 and 15.

Apparently there are other mechanisms acting that account for this creep reversal. The scatter of the points in Figure 14 indicates that, possibly, two mechanisms are at work in opposition to one another.

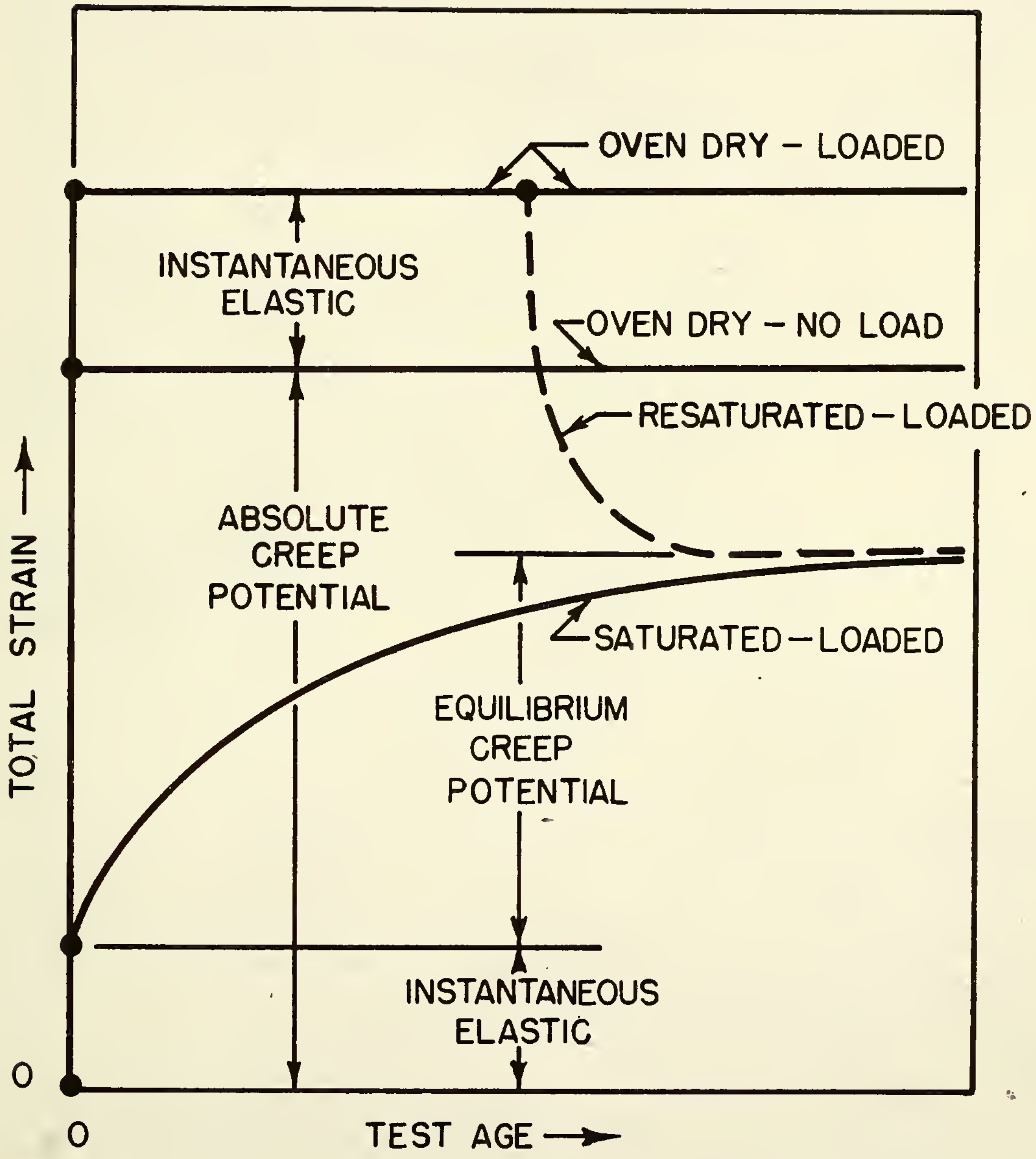

FIG. 19 CONCEPT OF CREEP POTENTIAL

Internal fracture due to resaturation is implied, followed by cycles of reorientation in the manner postulated to explain the scallop effect. In Figure 7, the resaturation specimen cracked visibly upon immersion. One attempt to vacuum resaturate an unloaded specimen resulted, literally, in disintegration when the specimen was flooded unevenly. In Figure 15, vacuum resaturation data are shown for a 0.45 water cement ratio specimen. Rapid expansion and creep reversal followed this short, severe resaturation process. At 500 hours, despite a decreasing creep rate, it seems evident that the original absolute creep potential will be exceeded, another indication that vacuum resaturation, as applied in this investigation, may induce specimen damage.

It is felt that the observation of creep reversal is an indication of the imperfection of the resaturation process and not a negation of the concept of equilibrium creep potential. Evidence is in the comparison of the reversal curves or Figures 6, 14, and 15, where severity of the reversal seems to be directly related to the rapidity of the resaturation process.

Thus, the resaturation exposure does not seem to be satisfactory, and to eliminate the creep reversal effect it should be made less severe. Possibly vacuum resaturation by water vapor until equilibrium is observed could be accomplished by evacuating the specimen over a reservoir of water. If all air could be exhausted from the system before admission of water vapor, saturation would occur in an almost pure water vapor atmosphere. Equilibrium reached in this environment should be the equilibrium creep potential.

Additional Expansion upon Unloading

When the various resaturated specimens were unloaded, additional time dependent expansion occurred, in excess of the elastic recovery. Such an expansion curve is shown in Figure 6. The indication is that a disturbance of the internal balance of forces acting on the adsorbed water takes place, and the system readjusts toward a new equilibrium by swelling. The new equilibrium creep potential should be one of zero strain level,, except that it will be raised by the amount of the irrecoverable deformation accumulated due to particle reorientation in the drying and creep reversal processes.

SUMMARY

The important findings of this investigation can be recapitulated as follows:

1. The combination of the periscope adaptation of the Monfore hypodermic needle tube strain gage with the 50X bifilar linear traversing microscope allowed the measurement of strains of the order of accuracy of 10 microinches per inch.

2. Hollow cylindrical paste specimens could be cast successfully by the use of external vibration with a wall as thin as 0.1 inch, an outside diameter 1.1 inches, and a height of 7 inches. This was demonstrated for pastes with water cement ratios ranging from 0.30 to 0.45.

3. The density of the test specimens could be controlled to a fairly uniform value by an inversion-reinversion and revibration process applied to the fresh paste specimens in sealed molds.

4. Use of the thin walled specimens resulted in a shortening of the test cycle in accord with the size effect and in comparison to investigations reported in the literature for specimens of larger dimension.

5. The time dependent strain data for sealed specimens exhibited three fairly distinct zones of curvature. The existence of these zones has been taken as evidence that there is more than one mechanism of creep functioning, and that the change from one zone to another is

indicative of the ascendency of one mechanism of creep and the attrition of another.

6. A scallop effect was found in the data for all individual saturated specimens. This scallop effect was most noticeable in the first of the three creep curve zones mentioned above, and is attributed to a cyclic combination of the seepage, delayed elastic, and mechanical reorientation theories of creep mechanism.

7. Creep recovery of saturated specimens was less than creep under load for an equal time. This is an implication that part of the creep is irrecoverable.

8. In every instance of loading, hardened paste specimens that were oven dried at 110 C to constant weight did not creep at all. This is regarded as evidence that there is an upper limit on time dependent deformation of hardened portland cement paste that is independent of applied load. This upper limit is equal to the drying shrinkage and is called the absolute creep potential.

9. The instantaneous elastic deformation of saturated specimens was, as a general rule, lower than that of comparison oven dried specimens. Since there was no time dependent strain of dry specimens, the differences between these two observed instantaneous elastic deformations is regarded as the delayed elastic deformation. The delay in achievement of this part of the elastic deformation is attributed to the action of the seepage mechanism theory of creep.

10. Upon the resaturation of oven dried specimens under load, a quasi-equilibrium level was found that is associated with the so-called equilibrium creep potential. The equilibrium creep potential is the

residual value of unrecovered shrinkage plus any delayed elastic deformation when the expansion of an oven dried specimen has reached its maximum value after having been rewetted to a given humidity and under a given load. The equilibrium creep potential is therefore load and humidity dependent. The maximum value of the equilibrium creep potential is the absolute creep potential.

11. A creep reversal effect was observed for specimens resaturated under load; whereupon, after reaching the equilibrium creep potential, expansion ceased and creep was observed. This effect is attributed to internal damage to the specimens sustained in a rather severe and abrupt wetting process.

12. The complete absence of creep in the dry specimens, the creep of saturated specimens loaded under water; the failure to observe an end point to saturated creep recovery; the time dependent expansion of dry specimens to an equilibrium upon resaturation; and the additional time dependent expansion of the resaturated specimens upon unloading, point to water as the major intrinsic factor in the time dependent deformation of cement paste, and to seepage as the dominant mechanism of creep. It is indicated that the mechanical reorientation and the delayed elasticity mechanisms of creep are also important.

13. The absence of creep when all shrinkage has taken place suggests that creep and shrinkage have the same mechanism and that creep is load induced shrinkage.

CONCLUSIONS

Based upon the results of this investigation, the following conclusions appear reasonable:

1. Oven dried hardened portland cement paste does not creep under applied load. Therefore water is the dominant intrinsic factor in the creep of this material. A logical deduction is that the most important mechanism of creep is seepage.

2. For hardened portland cement paste there exists an absolute creep potential or maximum upper limit on creep that is independent of load. The value of the absolute creep potential is the value of the oven dry shrinkage determined at the age of loading.

3. For hardened portland cement paste there probably is an equilibrium creep potential, which is load and moisture dependent. This equilibrium creep potential is defined here as the residual value of unrecovered shrinkage plus any delayed elasticity when the expansion of an oven dried paste has reached its maximum value after having been rewetted to a given humidity and under a given load. The maximum value of the equilibrium creep potential is the absolute creep potential.

4. The scallop effect is an indication of the existance of particle fracture and reorientation.

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VITA

VITA

WESLEY GRIGG MULLEN, BS, VMI, 1949; MS, U of Md., 1951; PhD, Purdue, 1963

Birthplace and Date: Richmond, Va.; November 30, 1922.

Citizenship: United States

Honors:
Distinguished Graduate - VMI;
Tau Beta Pi - U of Md.;
Sigma Xi - Purdue.

Graduate Fellowships:
National Ready Mixed Concrete Association, U of Md, 1949-51.
Asphalt Institute, U of Minn, Summer 1960
Portland Cement Association, Purdue, Summer 1961
American Society for Testing and Materials, Purdue, 1962-63

Professional Registration:
Maryland, New Jersey, New York, Virginia

Technical and Professional Membership:
ASTM, ACI, ASCE, HRB

Publications:
"Soil Separator", HRB Abstracts, May 1951.
"Effects of Temperature Changes on Concrete as Influenced by Aggregates", Walker, Bloem, and Mullen, Journal ACI, April 1952.
"Lightweight Concrete Deck for Tappan Zee Bridge Main Spans", Journal ACI, December 1958.

Experience:
Summer 1942 - Chainman, Pennsylvania RR.
1943-46 - 1st Lt, radar officer technician, USMC.
Summer 1949 - Resident inspector, sewage disposal complex, Town of Chase City, Virginia.
1949-51 - Graduate student and NRMCA Fellow, CE Dept, U of Md.
1951-59 - Resident engineer and concrete technologist, Madigan-Hyland, Consulting Engineers, Long Island City, New York. Work on Pier 57, Tappan Zee Bridge, New England Thruway, Garden State Parkway Connection for NYS Thruway, Berkshire Thruway, Castleton Bridge and consultation on concrete deterioration and repair work.
1959-61 - Instructor and graduate student, CE Dept., U of Md.
1961-62 - Instructor and graduate student, School of CE, Purdue
Part time research engineer, Joint Highway Res. Proj., Purd
1962-63 - Graduate student and ASTM Fellow, School of CE, Purdue.